

# Instruments for x- and $\gamma$ -ray astronomy

## Detecting x- and $\gamma$ -rays

[Detectors](#)

*[Gas-filled detectors](#)*

*[Scintillators](#)*

*[Semiconductors](#)*

## Telescope systems

[Geometric Optics](#)

[Quantum Optics](#)

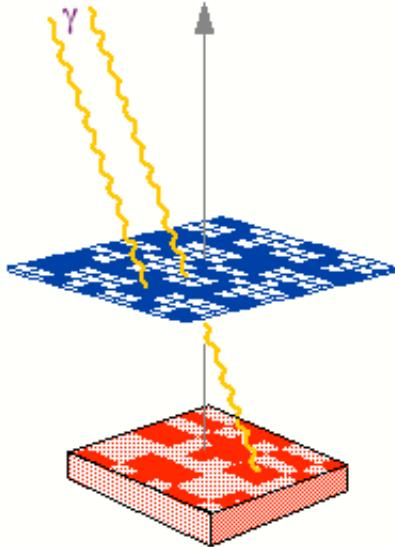
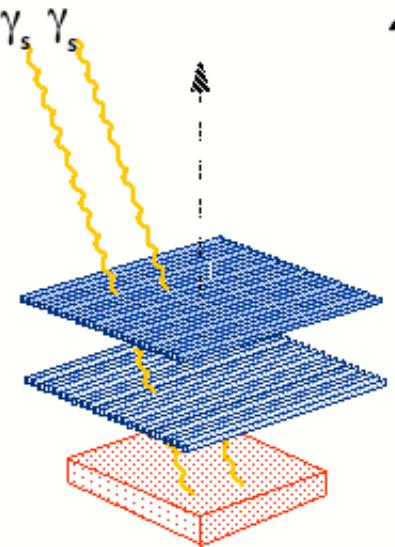
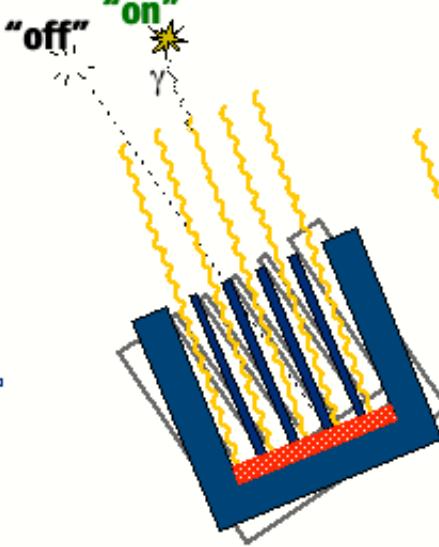
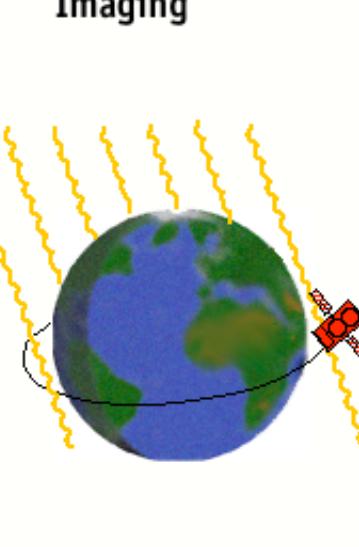
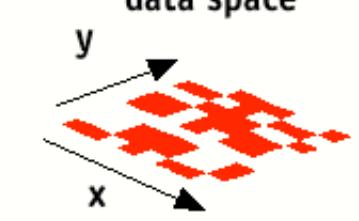
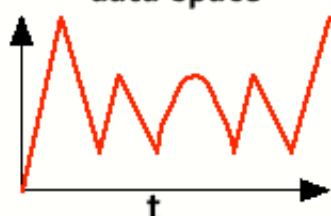
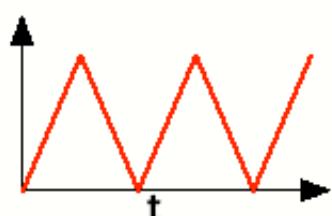
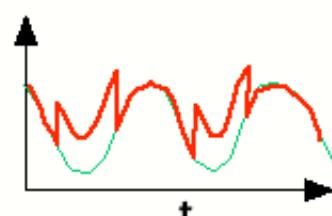
[Wave Optics](#)

# Instrument concepts in nuclear astrophysics

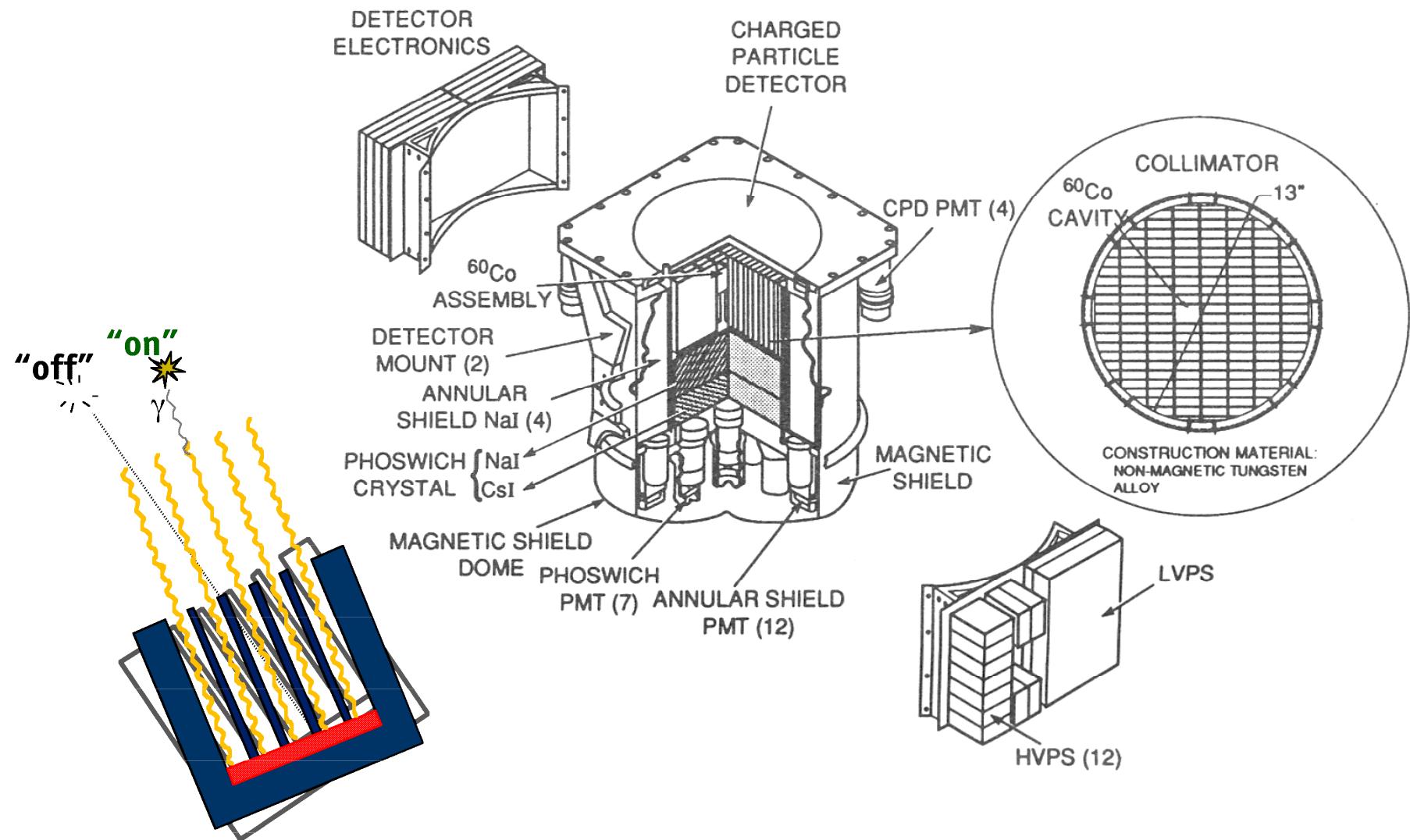
The instrumental categories in nuclear astrophysics reflects our current perception of *light* itself.

	<b>geometric optics</b> absorbtion	<b>wave optics</b> coherent scattering	<b>quantum optics</b> incoherent scattering
aperture detector			
	e.g. Coded mask telescopes	e.g. crystal lens telescopes	e.g. Compton telescopes

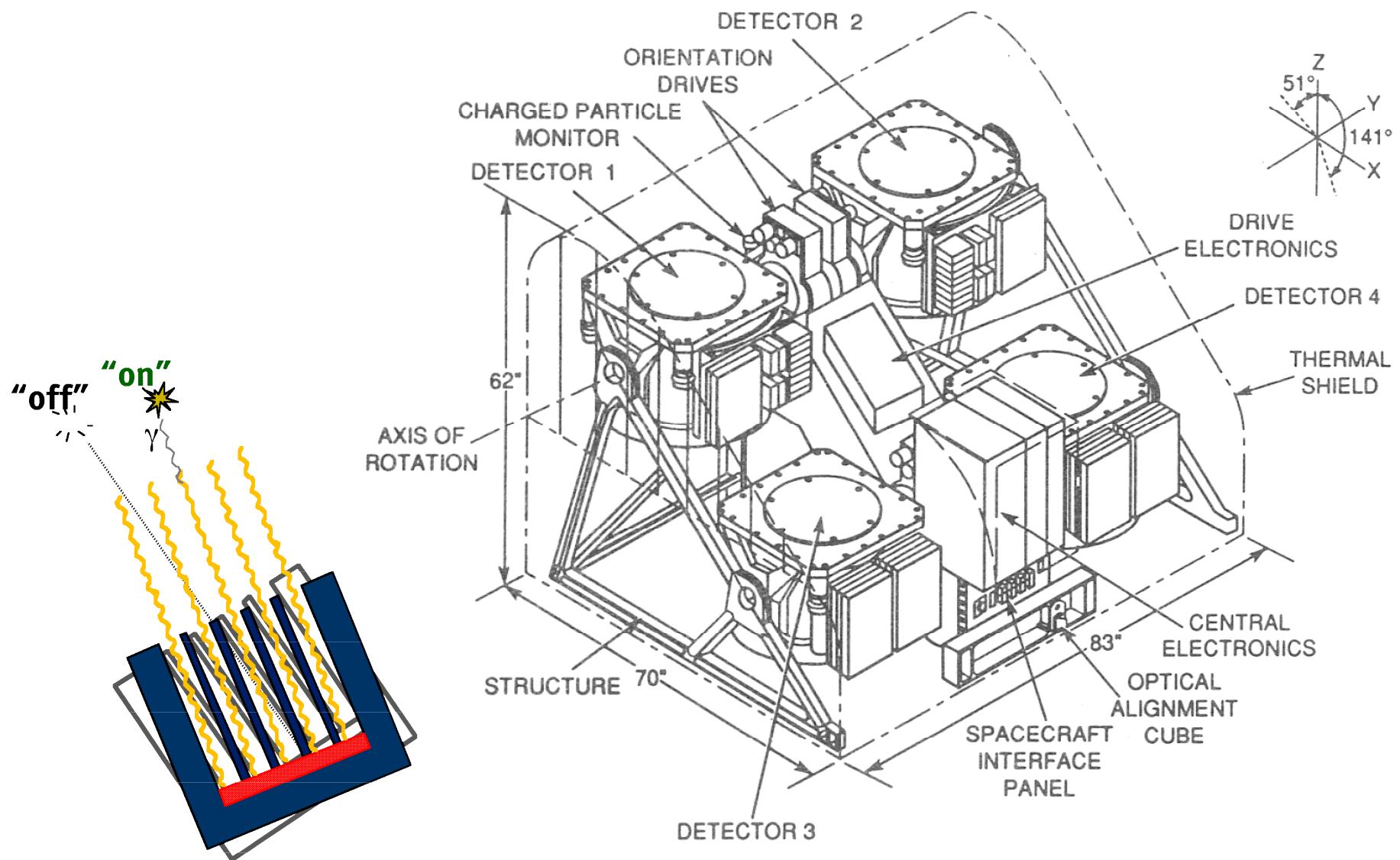
# Geometric Optics : Modulating Aperture Systems

spatial modulation	temporal modulation		
coded mask imaging 	rotating modulation collimator 	scanning collimator 	Occultation Transform Imaging 
data space 	data space 		

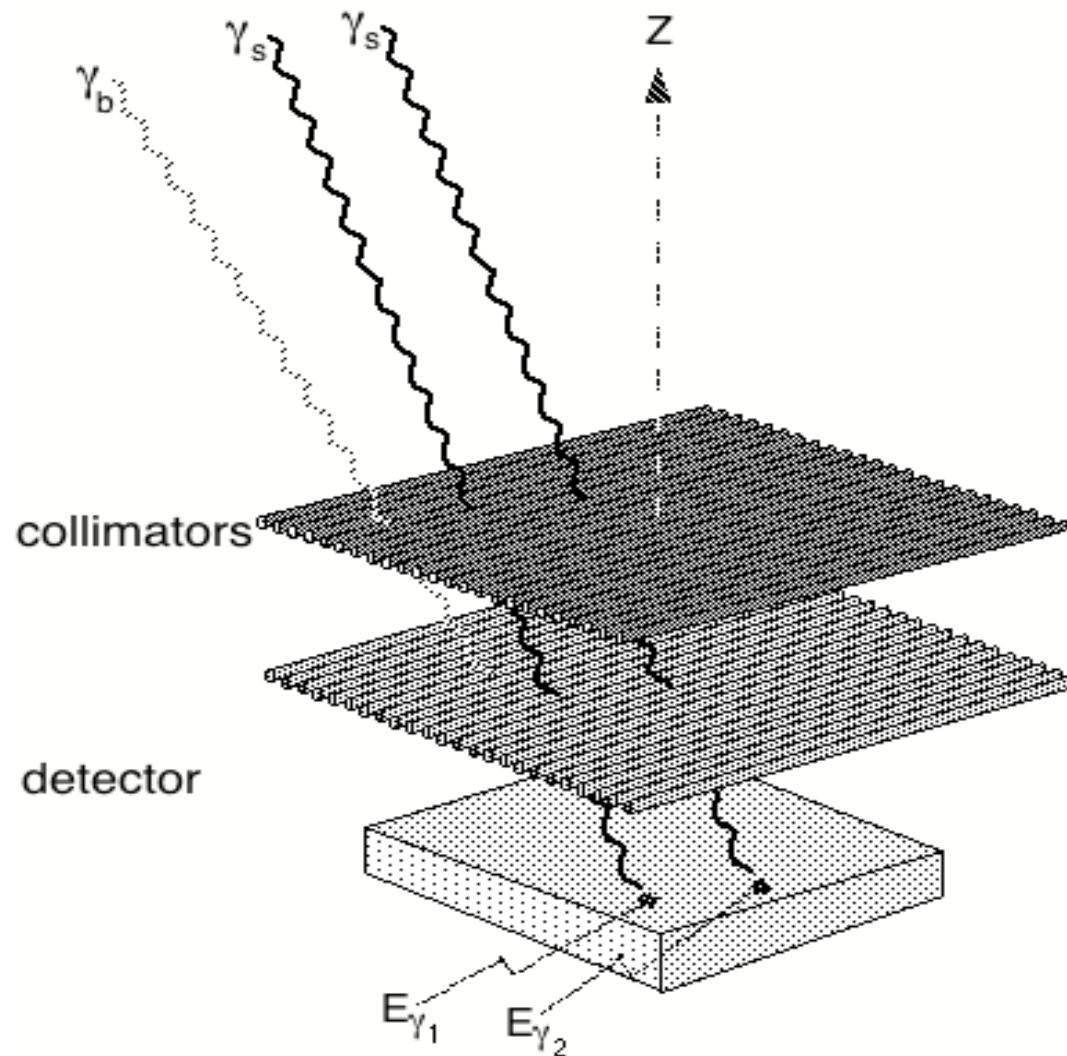
# Collimator "on" - "off" telescope : e.g. OSSE on CGRO



# Collimator "on" - "off" telescope : e.g. OSSE on CGRO



## temporal modulation of a point source with a bigrid (Oda)-collimator



*measured parameters :*

$E_\gamma$  : energy deposited  
t : arrival time

*expected count rate on detector :*

$$N'(t) = \sum_i s_i \cdot \varepsilon \cdot f_i(t) + B$$

$s_i$  : flux from the  $i^{th}$  source  
 $\varepsilon$  : detection efficiency  
 $f_i$  : transmission function for source  $i$  at time  $t$   
 $B$  : background count rate.

## temporal modulation of a point source with a bigrid (Oda)-collimator

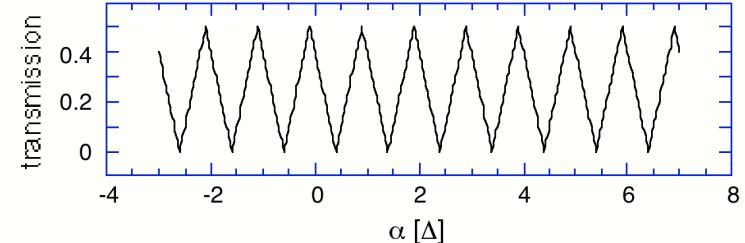
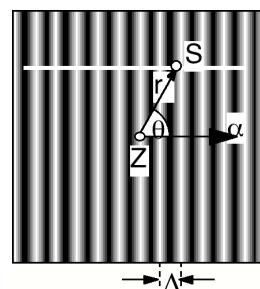
Transmission  $f_i$  for a point source located at the position  $r, \theta$  from the instrument z-axis

$$f_i = |0.5 - (|g_i - \text{int}(g_i)|)|$$

with  $g_i$  depending on the type of collimator movement and where  $\text{int}(g_i)$  is the integer part of  $g_i$

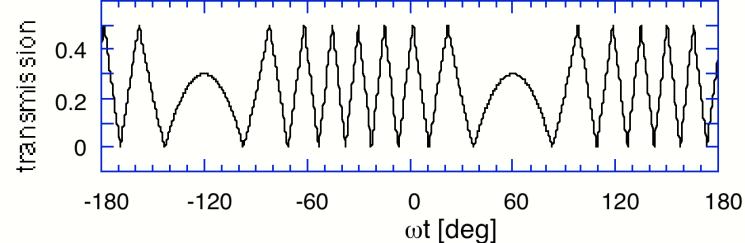
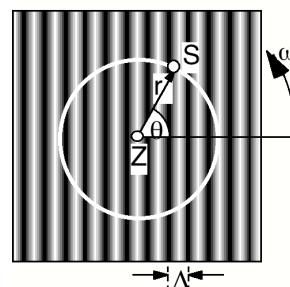
*scanning modulator*

$$g_i(\alpha) = \frac{r \cdot \cos(\theta) - \alpha}{\Delta}$$



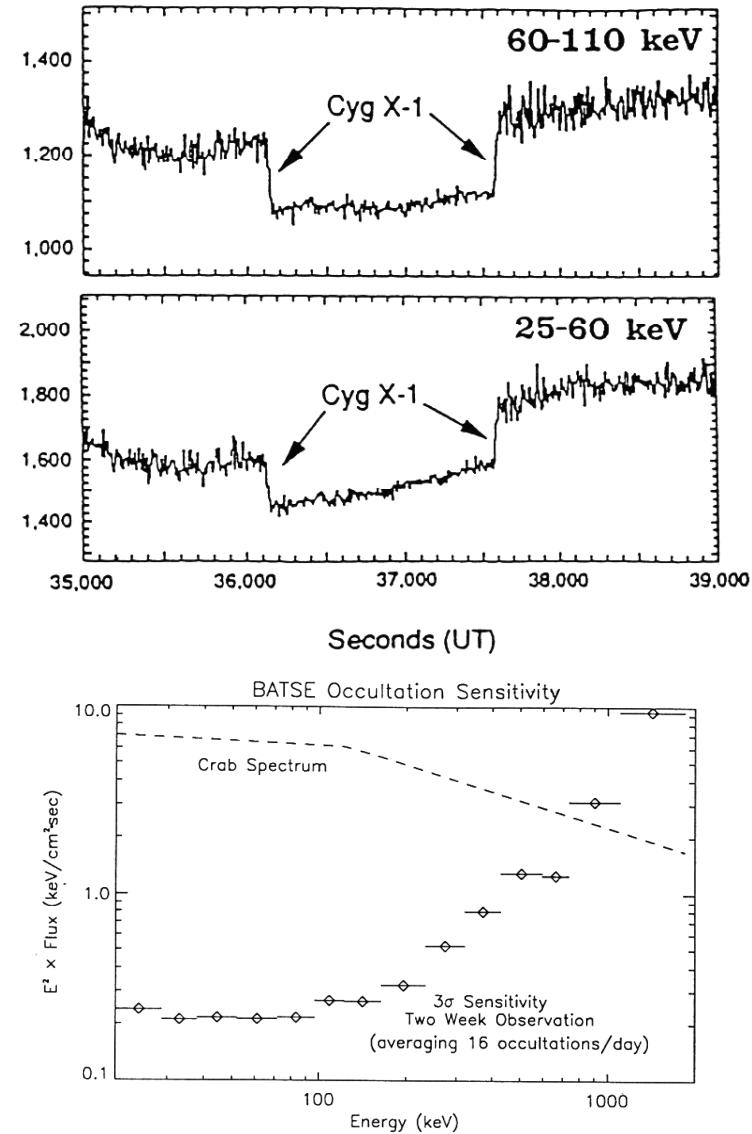
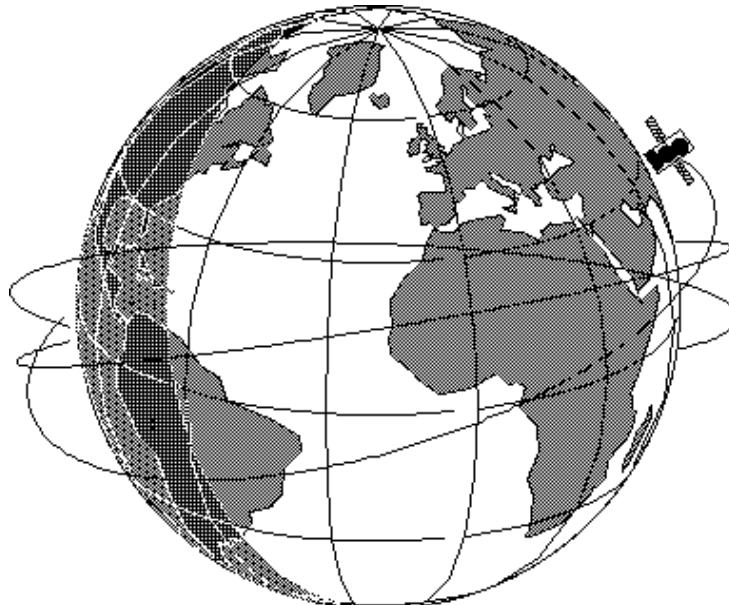
*rotating modulator*

$$g_i(\alpha) = \frac{r \cdot \cos(\theta - \omega t)}{\Delta}$$

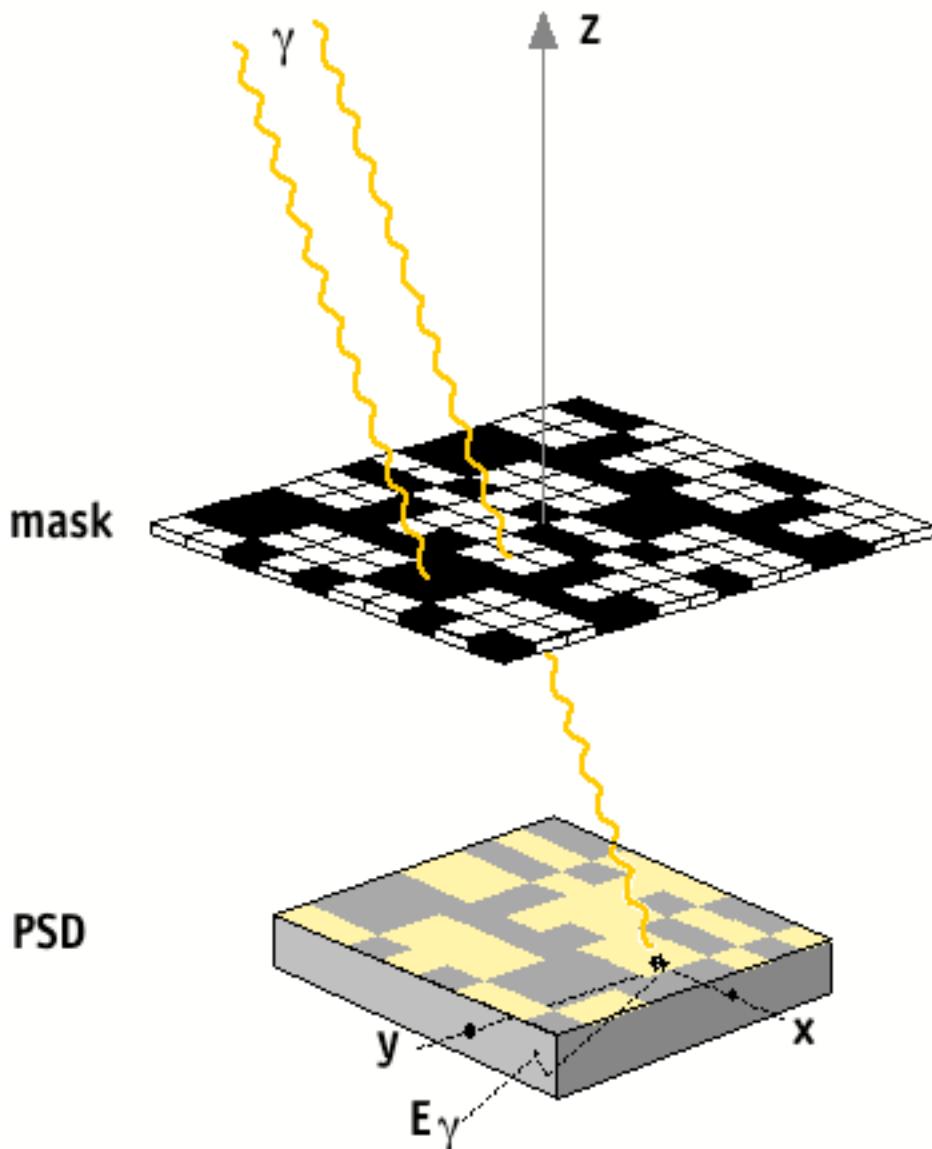


# Occultation Transform Imaging (BATSE)

with the planet earth as  
'rotation' modulation collimator  
(or scanning anti-collimator)



# coded mask imaging



*measured parameters :*

$x, y$  : int. location on the detector  
 $E_\gamma$  : energy deposited  
 $t$  : arrival time

astronomy : encoding of a two dimensional source distribution  $(i,j)$  into a 2-D dataspace  $(k,l)$

for sources at finite distance (nuclear medicine, tomography of X-ray emitting plasmas) coded mask techniques can be used to extract depth information for volumetric object reconstruction.

Why is it ...



Cargèse, 5 April 2006



instrumentation

## Aristotle and the coded mask

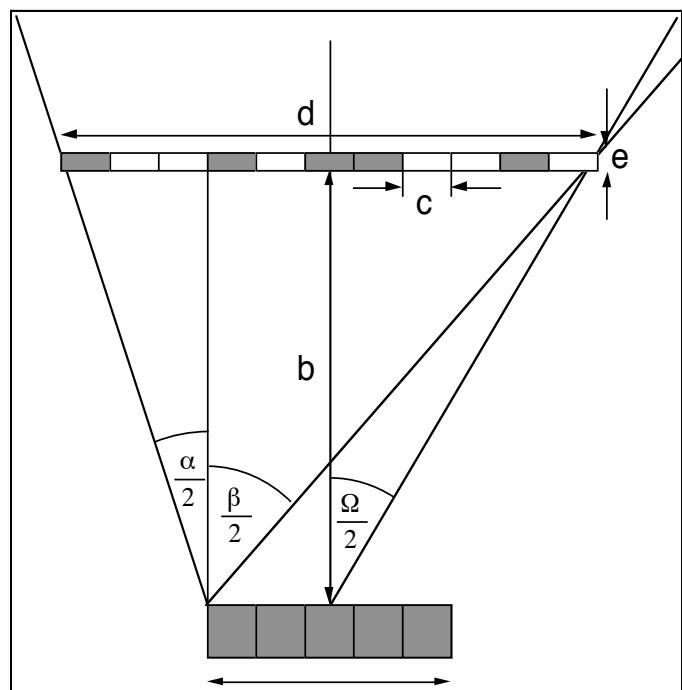
“Why is it that when the sun passes through quadrilaterals, as for instance wickerwork, it does not produce a figure rectangular in shape but circular ?”

Aristotle, problemata physica - problem XV,6

“Why is it that in an eclipse of the sun, if one looks at it through a sieve or through leaves, such as a planetree or other broad leaved tree, or if one joins of one hand over the fingers of the other, the rays are crescent-shaped where they reach the earth ? Is it for the same reason as that when light shines through a rectangular peep-hole, it appears circular in the form of a cone ? The reason is that there are two cones, one from the sun to the peephole and the other from the peep-hole to the earth, and the vertices meet ...”

Aristotle, problemata physica - problem XV,11

# Field of view characteristics of a coded mask instrument



FOV (FWHM)

$$\Omega = 2 \operatorname{arctg} \frac{d}{2b}$$

fully coded FOV

$$\alpha = 2 \operatorname{arctg} \frac{d-a}{2b}$$

partially coded FOV

$$\beta = 2 \operatorname{arctg} \frac{a+d}{2b}$$

angular resolution

$$\Delta\theta = r \Delta\theta' \\ = r \operatorname{arctg} \frac{c}{b}$$

vignetting

e, b, z from z axis

## coded mask imaging : *Encoding*

The intensity measured by the PSD can be expressed as a two-dimensional matrix  $D_{i,j}$  (the shadowgram) presenting the number of interactions registered in the detector element  $i,j$ .

$$D_{k,l} = \sum_{i,j} S_{i,j} \cdot A_{i+k, j+l} + B_{k,l}$$

$S_{i,j}$  : matrix of the source distribution,

$A_{i,j}$  : aperture transmission function  
(1 for transparent mask elements,  
0 for opaque elements)

$B_{i,j}$  : background noise matrix  
(all contributions not modulated by the aperture)

## coded mask imaging : *Decoding*

direct deconvolution :

correlate the encoded matrix D with decoding array G (postprocessing array)

$$S'_{i,j} = \sum_{k,l} D_{k,l} \cdot G_{i+k, j+l}$$

Substituting the encoded matrix D results in

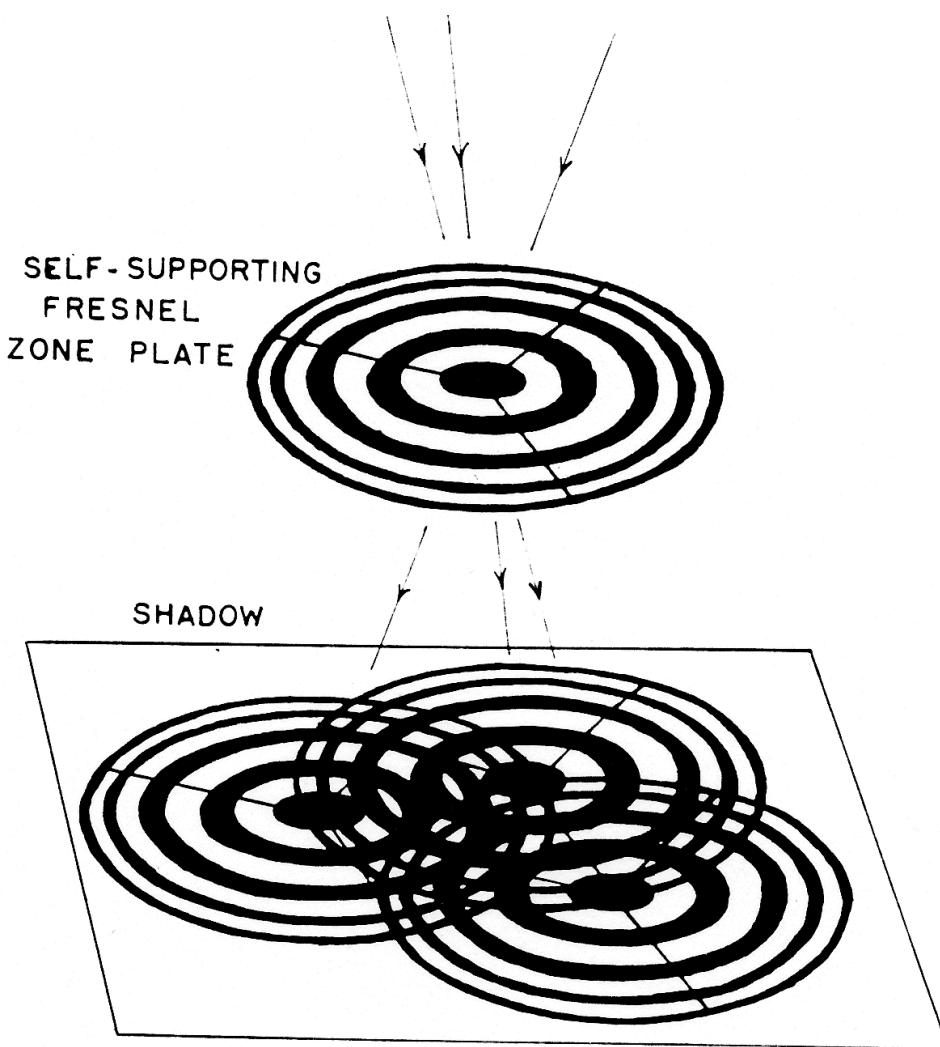
$$S' = (S * A) * G + B * G$$

$A^*G$  is the point spread function (PSF). Optimal mask patterns produce delta function  $A^*G = \delta$

$$S' = S + B * G$$

=> source is perfectly reconstructed with the exception of a background term.

# “X-ray star camera”

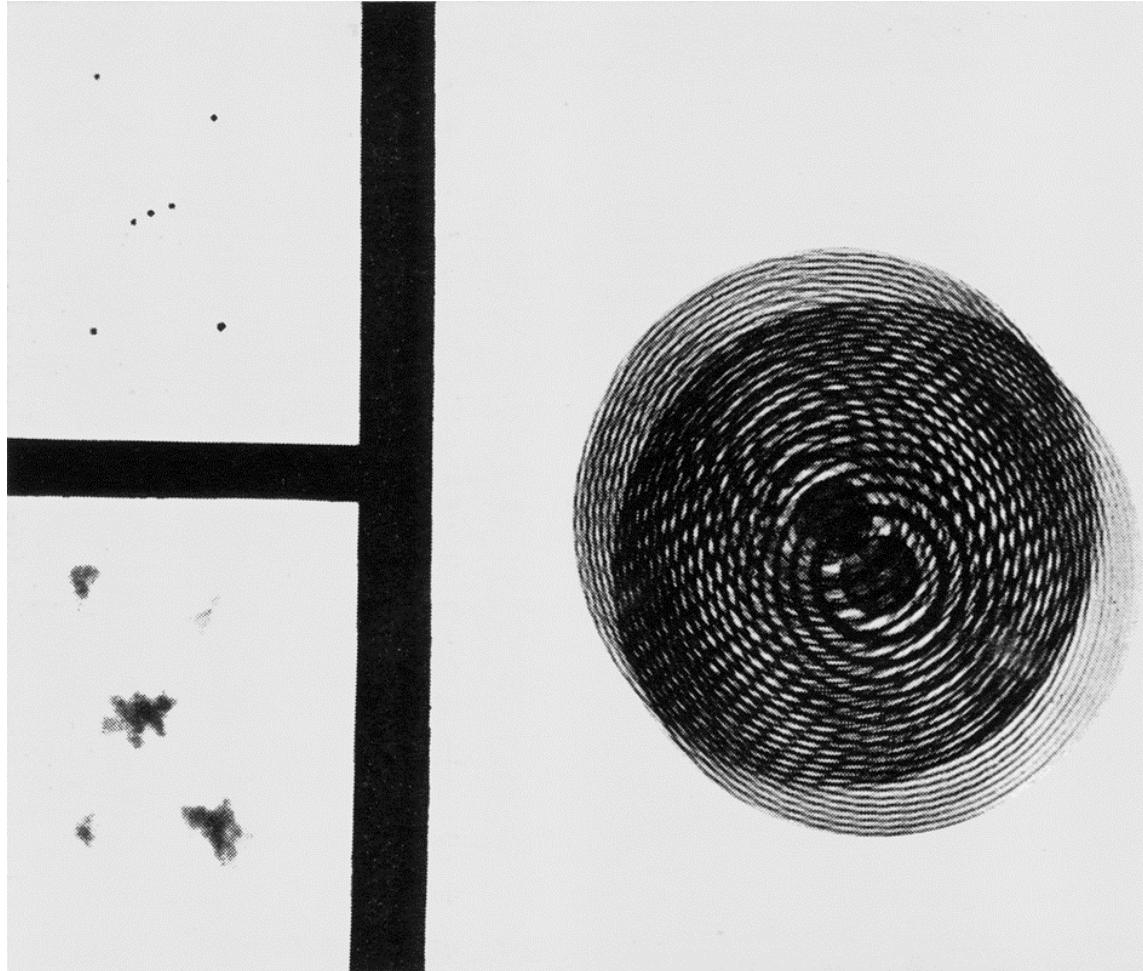


Fresnel Zone Plate = Mask

→ Shadowgram = Hologram

Mertz & Young, 1961

# “Illustrative sample of optical Fresnel transformation”



Mertz and Young's demo of the principle using visible light :

*upper left : source*  
illuminated pinholes simulate the n stars

*right : hologram*  
a Fresnel zone plate casts n distinct shadows

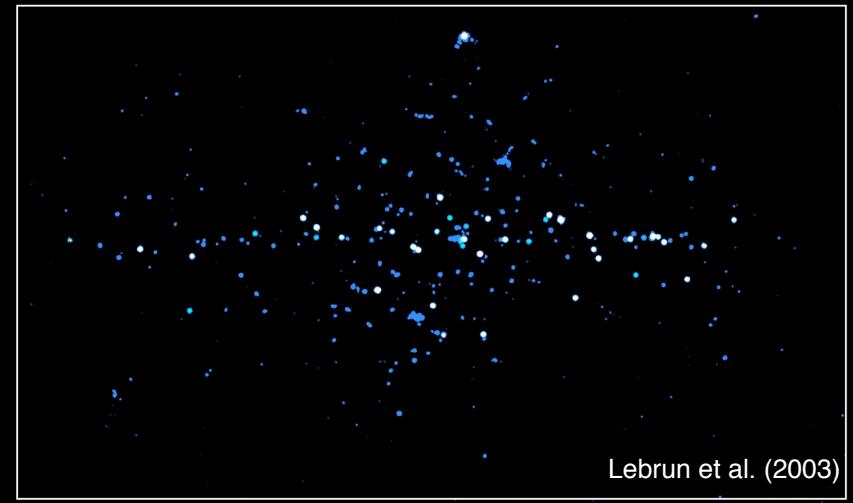
*lower left : image*  
reconstructed by diffraction from a reduced copy of hologram

Mertz & Young, 1961

# INTEGRAL

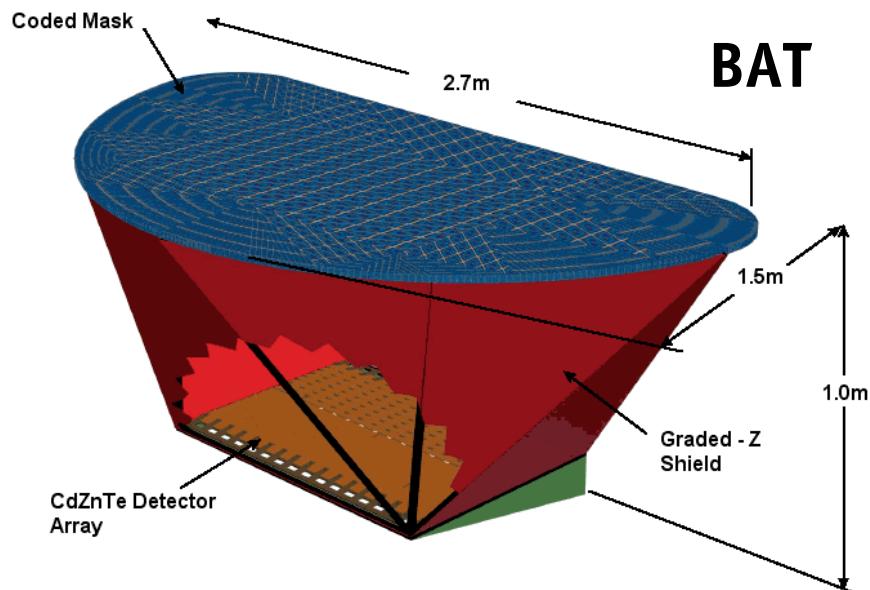


INTEGRAL



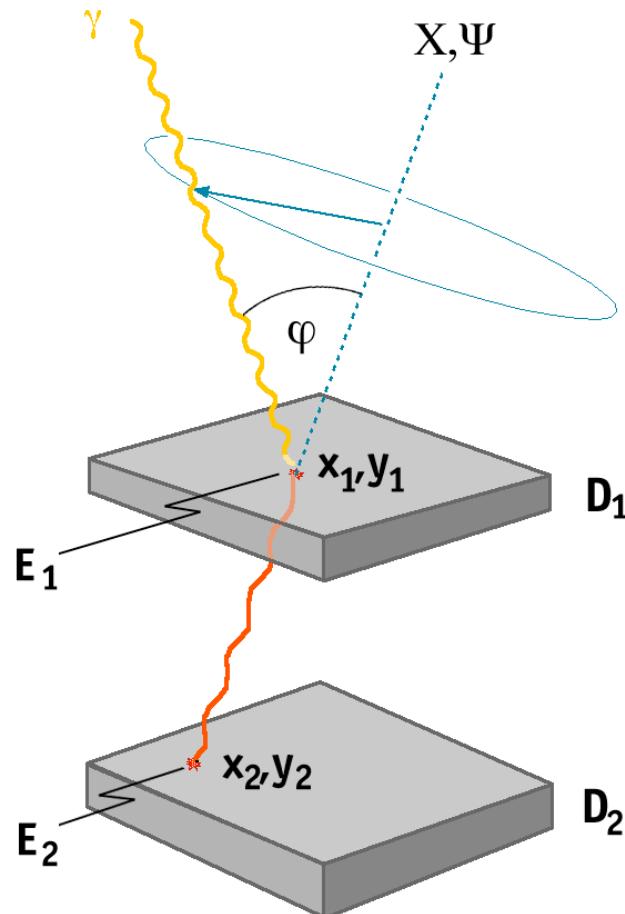
Lebrun et al. (2003)

# SWIFT



Detecting Area	5200 cm <sup>2</sup>
Detector	CdZnTe
Field of View	2 sr (half-coded)
Detection Elements	256 modules of 128 elem.
Detector Size	4 mm x 4 mm x 2 mm
Telescope PSF	22 arcmin
Energy Range	10-150 keV
Launch	July 2004 !

# Quantum Optics : e.g. Compton Telescopes



*measured parameters :*

- $x_1, y_1$  : interaction location in  $D_1$
- $E_1$  : energy deposit in  $D_1$
- $x_2, y_2$  : interaction location in  $D_2$
- $E_2$  : energy deposit in  $D_2$
- $t, \Delta t$  : arrival time, TOF  $D_1-D_2$

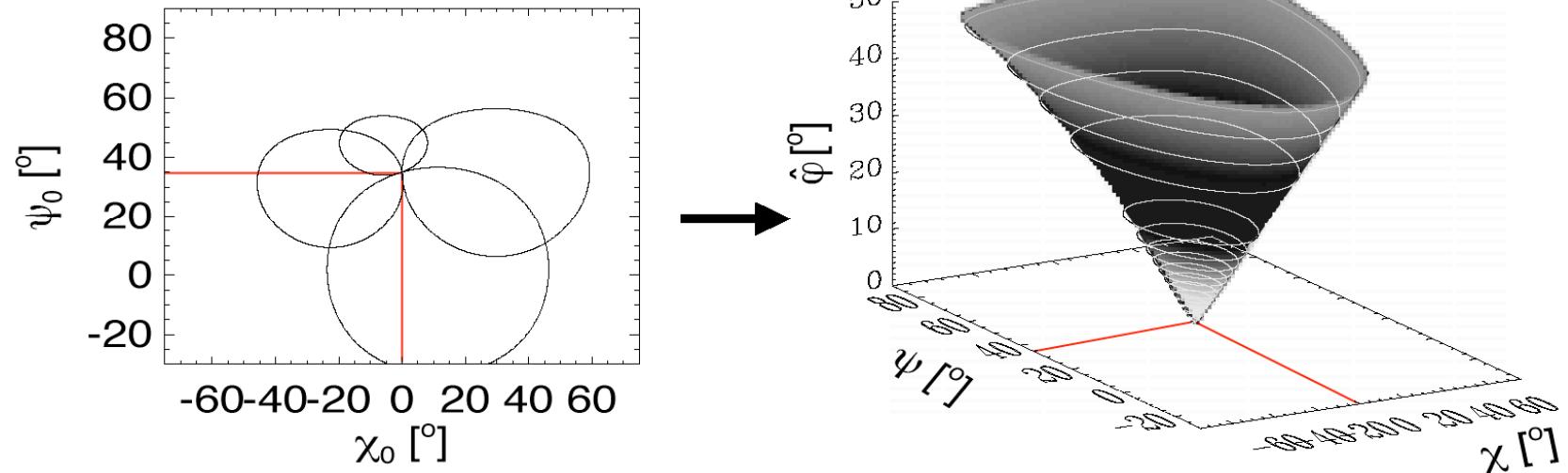
*derived parameters :*

$$\begin{aligned} x_1, y_1, x_2, y_2 &\Rightarrow \underline{\chi}, \underline{\Psi} \\ E_1, E_2 &\Rightarrow \underline{\varphi} \end{aligned}$$

$$\cos \underline{\varphi} = 1 - m_e c^2 / E_2 + m_e c^2 / E_1 + E_2$$

encoding of the two dimensional source distribution into a 3-D dataspace ( $\underline{\chi}, \underline{\Psi}, \underline{\varphi}$ )

# the dataspace of classical Compton telescopes

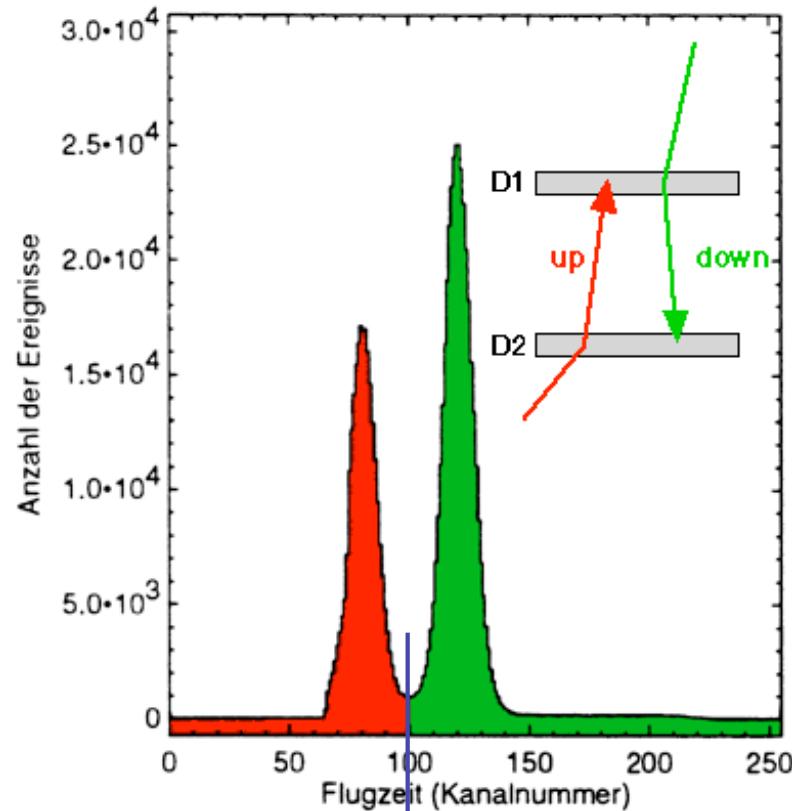


Eventcircles from a single pointsource  
at  $\chi, \psi$  ( $35^\circ, 0^\circ$ )

events from same pointsource lie on  
a cone with apex at  $\chi, \psi$  ( $35^\circ, 0^\circ$ )  
grayscale -> probability density  
(for 1.8 MeV photons, max. at  $O(j,-) =$   
 $23,7^\circ$ )

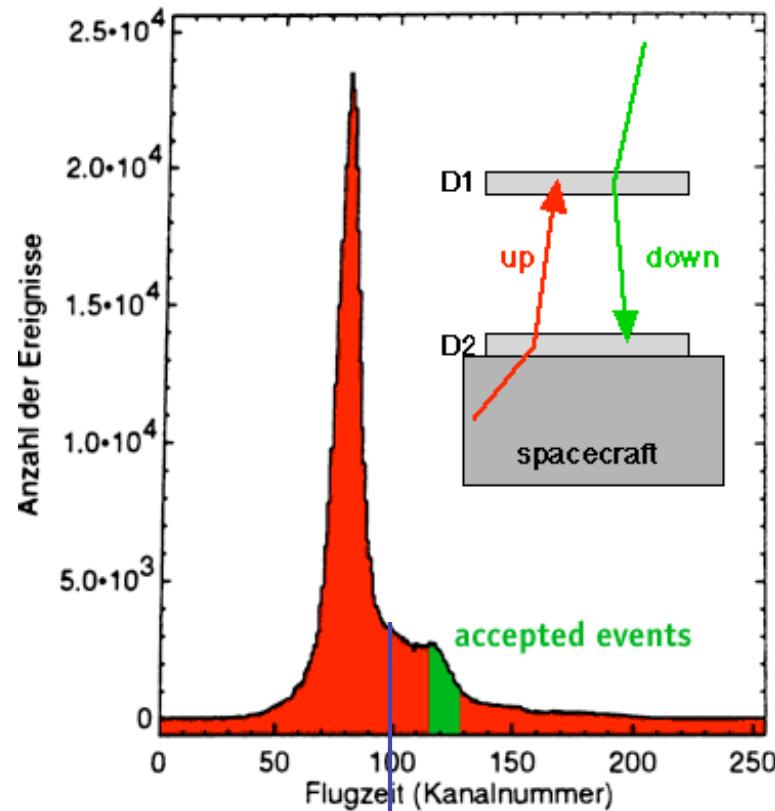
# Time of Flight coincidence (TOF)

# COMPTEL data



<- upward downward ->  
COMPTEL calibration data

channel width : 0.25 ns  
distance D1-D2 : 1.5 m  $\approx$  5 ns)

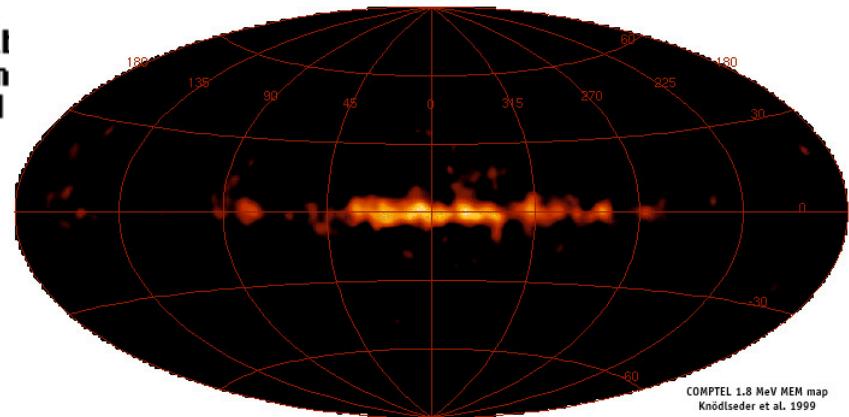
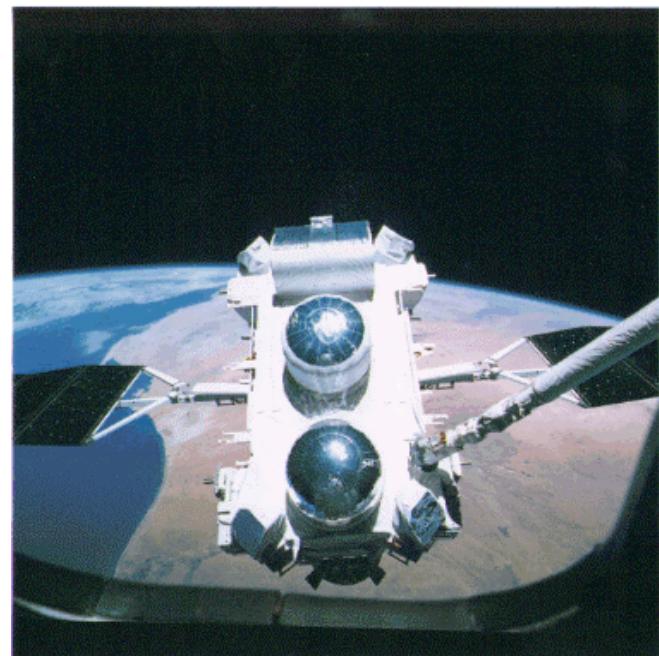
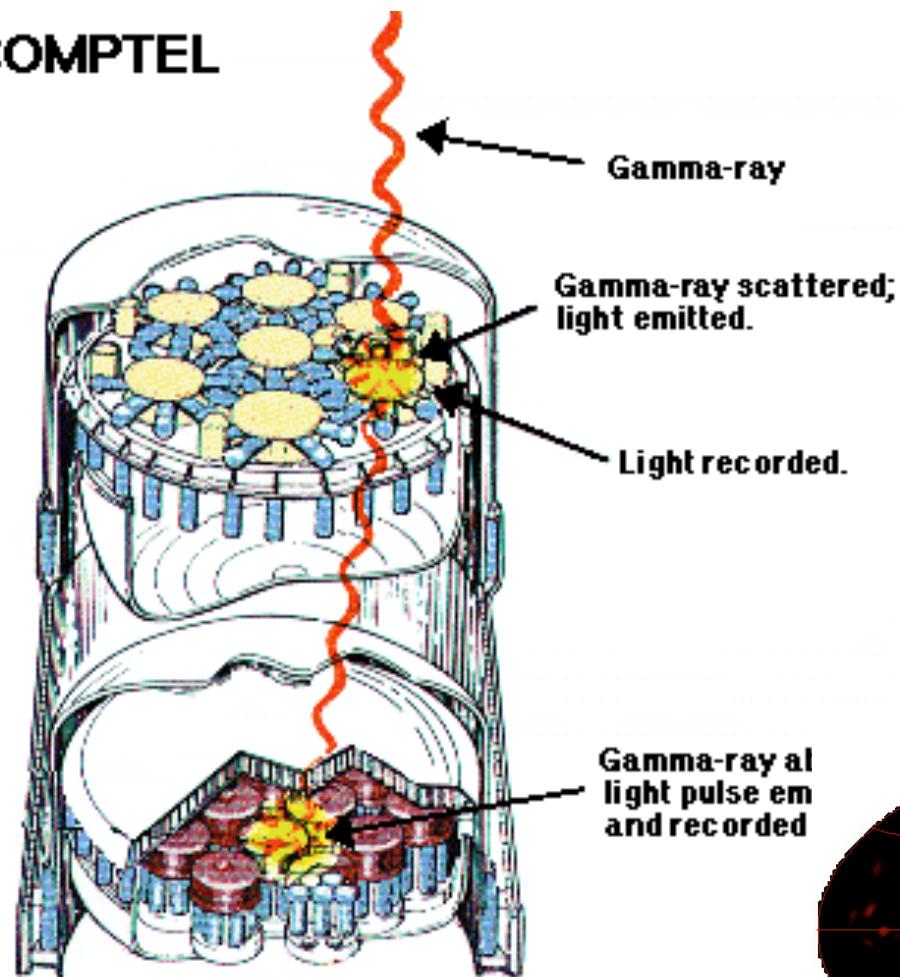


<- upward downward ->  
COMPTEL flight data

channel width : 0.25 ns  
“upward BG” from spacecraft and the Earth

# GRO COMPTEL

**COMPTEL**

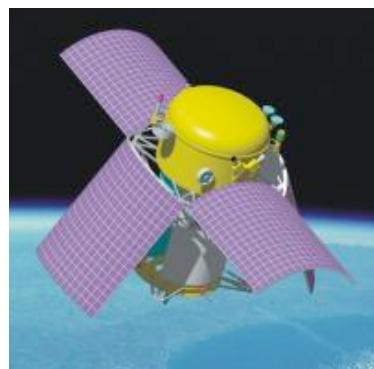


# Advanced Compton Telescope (ACT) options

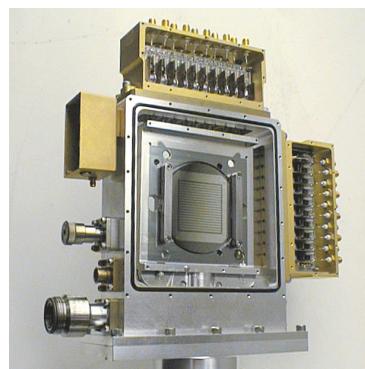
PROPERTY	CZT STRIP	Si STRIP	Ge STRIP	LIQUID Xe	Xe $\mu$ WELL
$\Delta E/E$ (1 MeV)	1%	0.2-1%	0.2%	4.5%	1.7%
Spatial Resolution	<1mm <sup>3</sup>	<1mm <sup>3</sup>	<1mm <sup>3</sup>	<1mm <sup>3</sup>	0.2 mm <sup>3</sup>
Stopping Power (Z, density)	48 8.3 g/cm <sup>3</sup>	14 2.3 g/cm <sup>3</sup>	32 5.3 g/cm <sup>3</sup>	54 3.0 g/cm <sup>3</sup>	54 0.02 g/cm <sup>3</sup> (3 atm)
Volume (achieved)	4 cm <sup>3</sup>	60 cm <sup>3</sup>	130 cm <sup>3</sup>	3000 cm <sup>3</sup>	50 cm <sup>3</sup>
Operating T	10° C	-20° C	-190° C	-100° C	20° C
Application	calorimeter	scatterer	scat/cal	scat/cal	scatterer
Institutions	UNH, UCSD	NRL, UCR	Berkeley, NRL	Columbia, Rice	GSFC



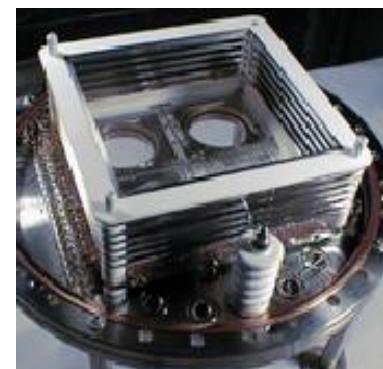
TIGRE  
UC Riverside



MEGA  
MPE, UNH



Ge-ACT  
UC Berkeley



Liquid XE  
Columbia

## ACT science requirements

<b>Energy Range</b>	0.2 – 30 MeV Compton mode
<b>Energy Resolution</b>	<10 keV FWHM @ 1 MeV
<b>Field of View</b>	>4 steradian
<b>Angular Resolution</b>	1°
<b>Source Localization</b>	5' bright sources
<b>Line Sensitivity</b>	$1 \times 10^{-7} \text{ cm}^{-2}\text{s}^{-1}$ in $10^6 \text{ s}$ (narrow)
	$5 \times 10^{-7} \text{ cm}^{-2}\text{s}^{-1}$ (broad)
<b>Continuum Sensitivity</b>	$1 \times 10^{-9} \text{ cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}$ @ 0.5 MeV
<b>Polarization Sensitivity</b>	1%, $2 \times 10^{-3} \text{ cm}^{-2}\text{s}^{-1} \text{ MeV}^{-1}$ 10% $2 \times 10^{-4} \text{ cm}^{-2}\text{s}^{-1} \text{ MeV}^{-1}$

# Sensitivity

Variance  $V$  of a signal at the limiting flux  $f_n$

$$V = (f_n \cdot X + N)^{1/2}$$

$N$  : number of equivalent total background counts,  $X$  : exposure.

$$\begin{aligned}N &= N_{\text{on}} + \alpha^2 N_{\text{off}} \\&= 2 \cdot A_{\text{on}} \cdot h \cdot \Delta E \cdot T_{\text{obs}} \cdot s_{\text{off}} \quad \text{for } \alpha = 1 \\X &= A_{\text{on}} \cdot T_{\text{obs}} \cdot t \cdot m \cdot e_{\text{fep}} \cdot s\end{aligned}$$

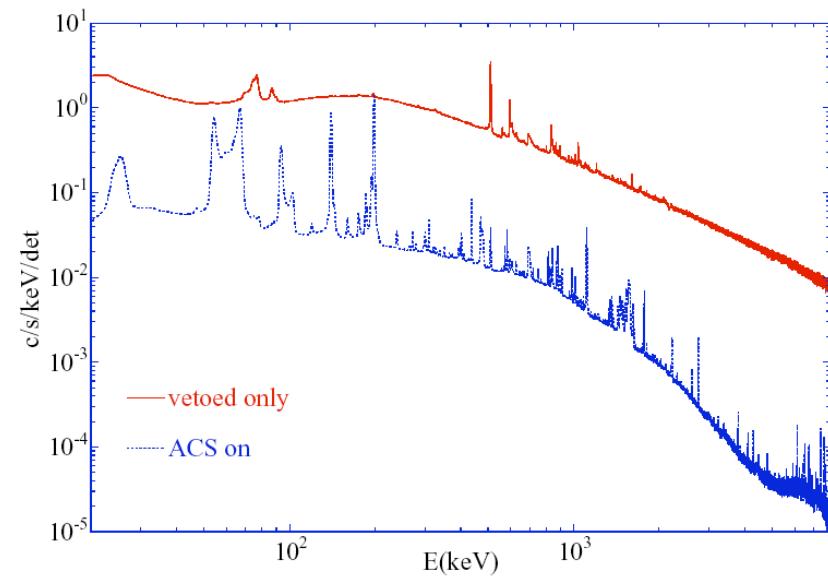
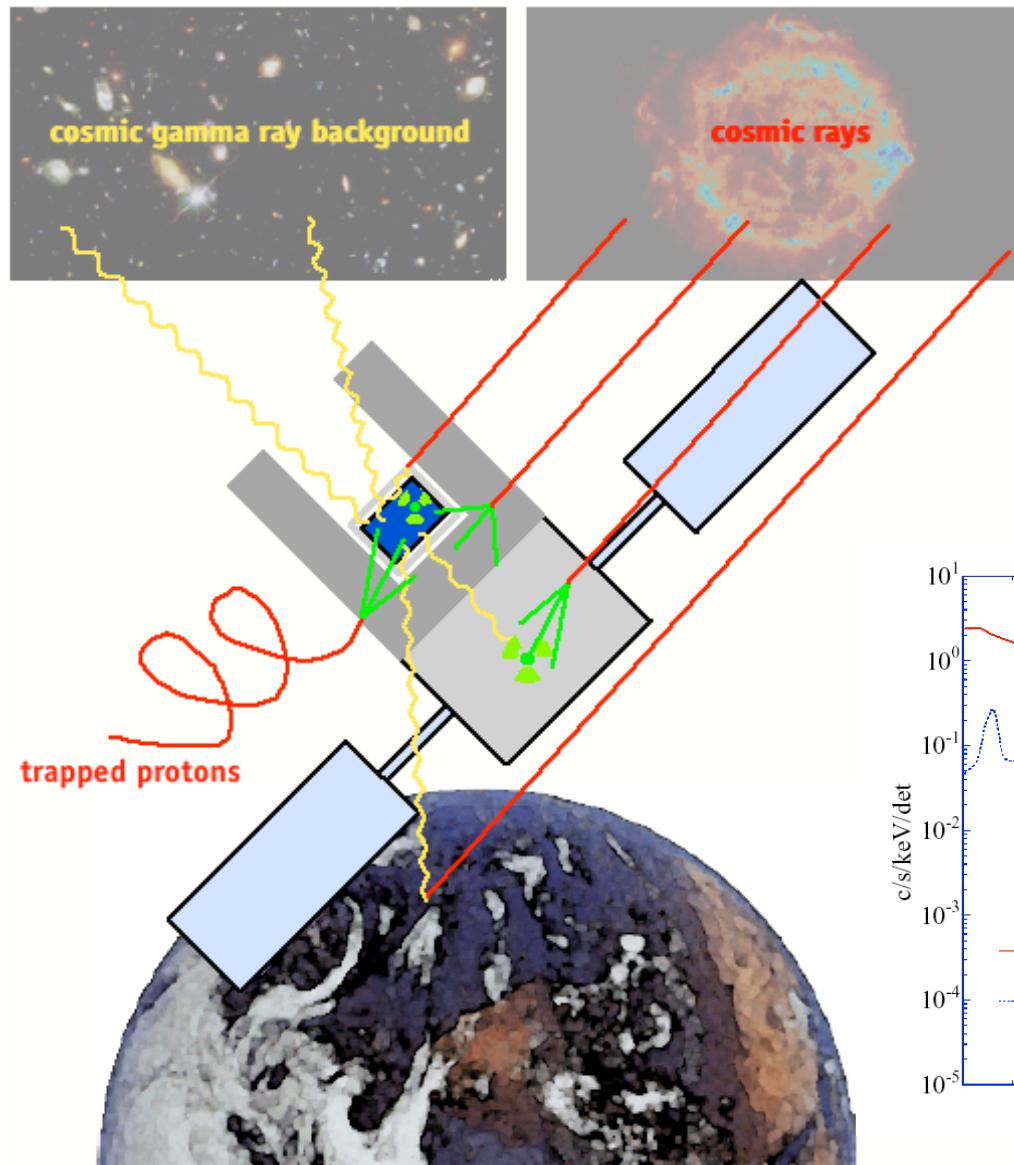
The  $\gamma$ -ray source flux will be detected at  $n$  standard deviations is

$$\begin{aligned}f_n &= n \cdot (f_n \cdot X + N)^{1/2} / X \\&\approx n \cdot N^{1/2} / X \quad \text{for } f_n \cdot X \ll N : \text{weak source limit.}\end{aligned}$$

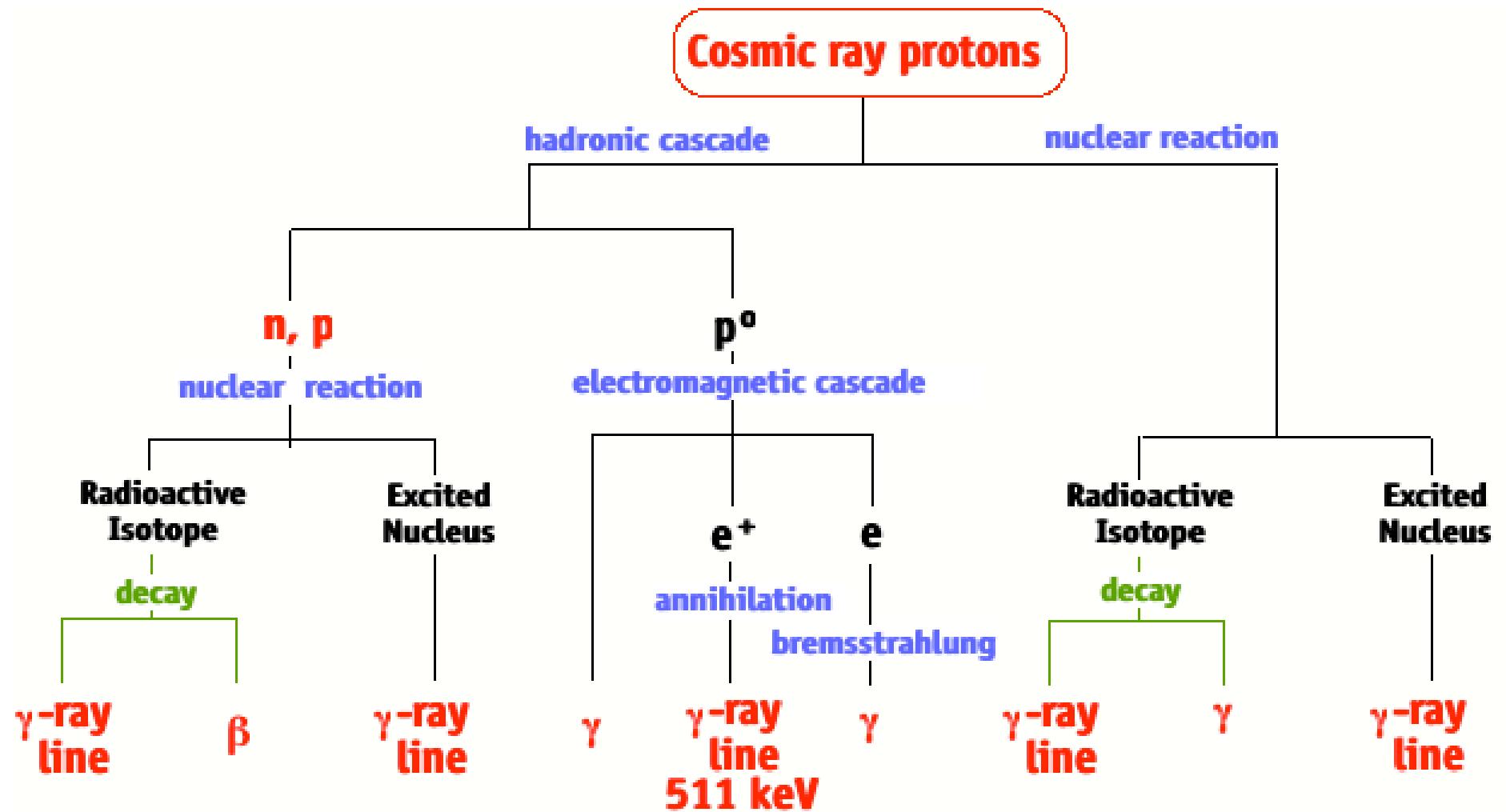
Case of a low background,  $\omega = (1.5 / N^{1/2})$  becomes different from  $\sim$  zero  $\Rightarrow$

$$f_n = (n \cdot N^{1/2} / X) \cdot [1 + \omega + 1/2\omega^2 + O(\omega^4)] \text{ with } \omega := n/2 \sqrt{N}$$

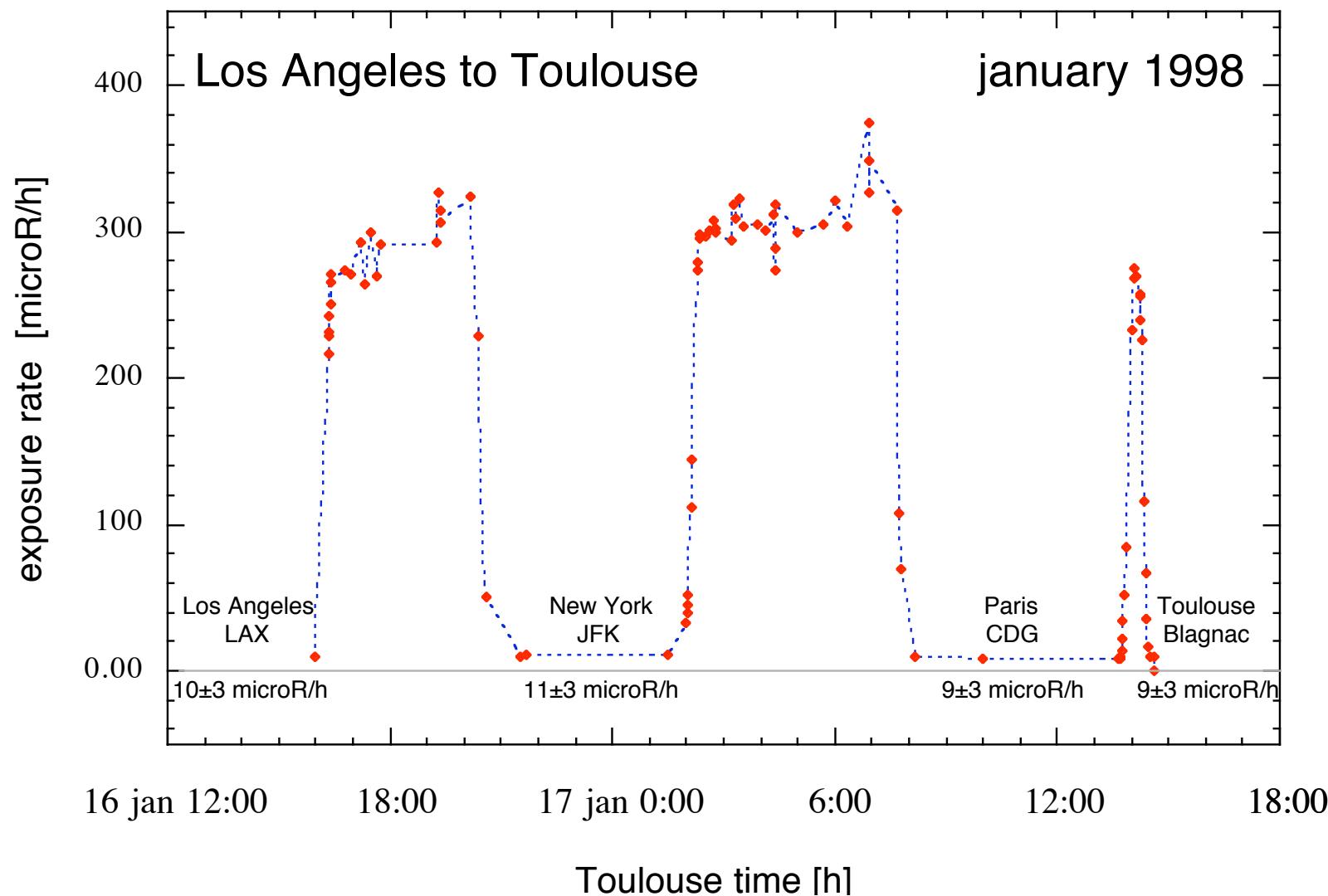
# Background



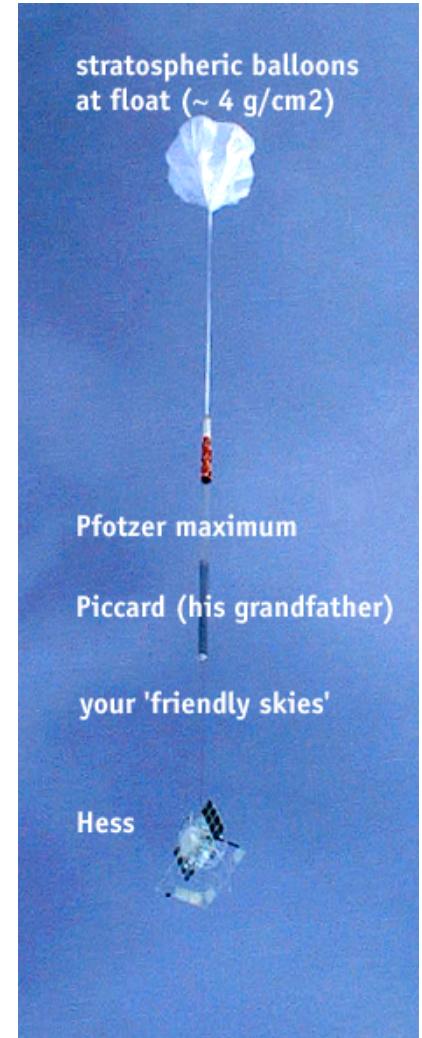
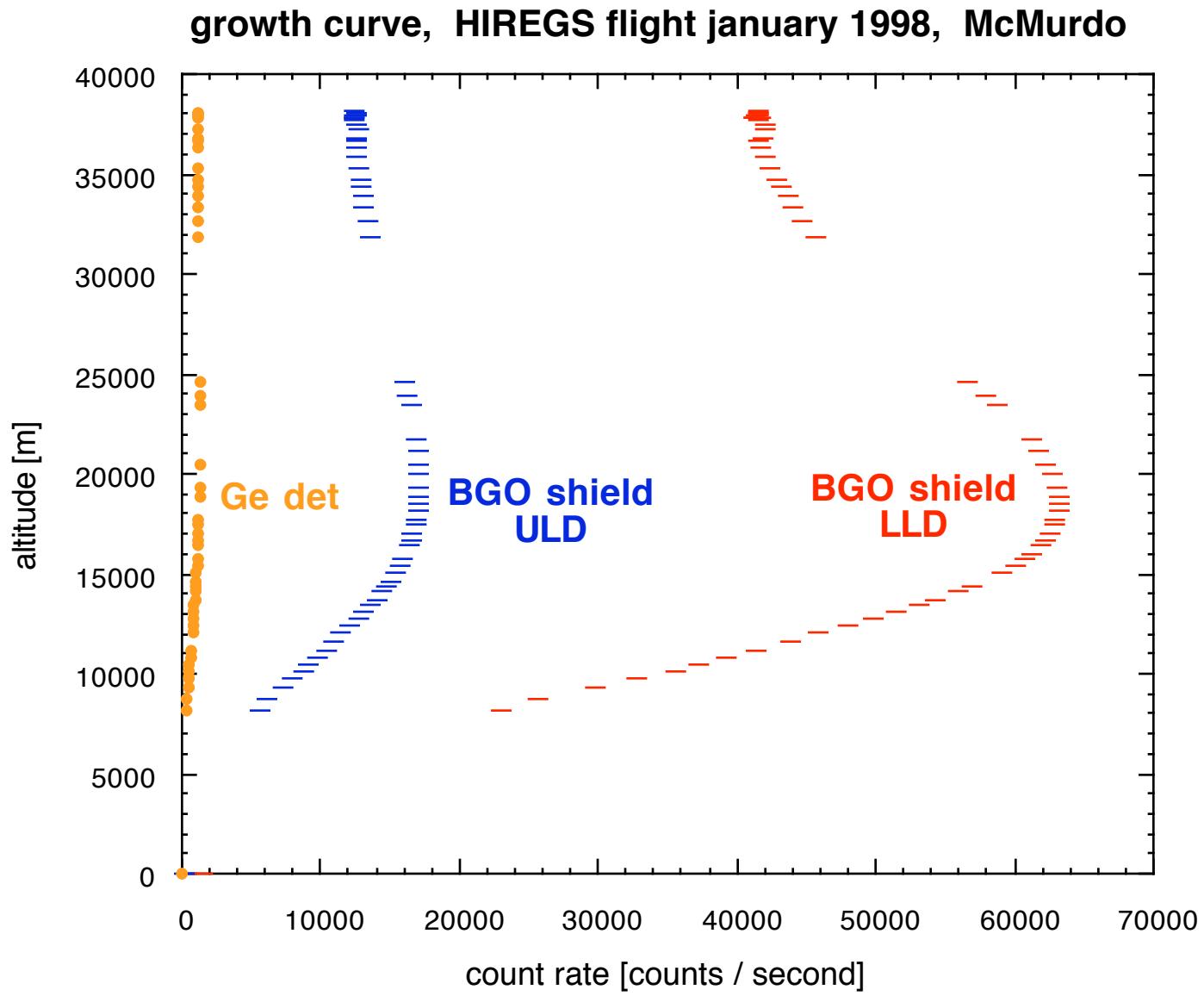
# Cosmic Ray interactions and $\gamma$ -ray background



# The background of our friendly skies ...



# Background - $\gamma$ -Ray production within the atmosphere



# Living with background - strategies

## A : fight

passive shielding

active anticoincidence shields

supershields

discrimination of BG-event signatures      e.g.

- phoswich
- pulse shape discrimination (PSD)
- time of flight measurements (TOF)

## B : avoid

choice of orbit (e.g. high cutoff rigidity, avoiding radiation belts)

minimize passive mass

choice of low BG materials (e.g.  $^{70}\text{Ge}$ )

solid angle effects (earth -> high orbit, spacecraft -> mast)

coincidence techniques (Compton telescopes, TPC's)

small detectors (focusing)

resolution (spectral-, angular-, timing)

## Background - Anticoincidence Shield

background reduction, shields against

- prompt CR interactions
- cosmic diffuse gamma-ray component
- $\gamma$ -rays generated in the atmosphere / spacecraft

defines a field of view

improves spectral response function

- “Anti-Compton” rejection of source events not in full energy peak
- Rejection of source events  $>m_e c^2$  in the escape peaks

background generator

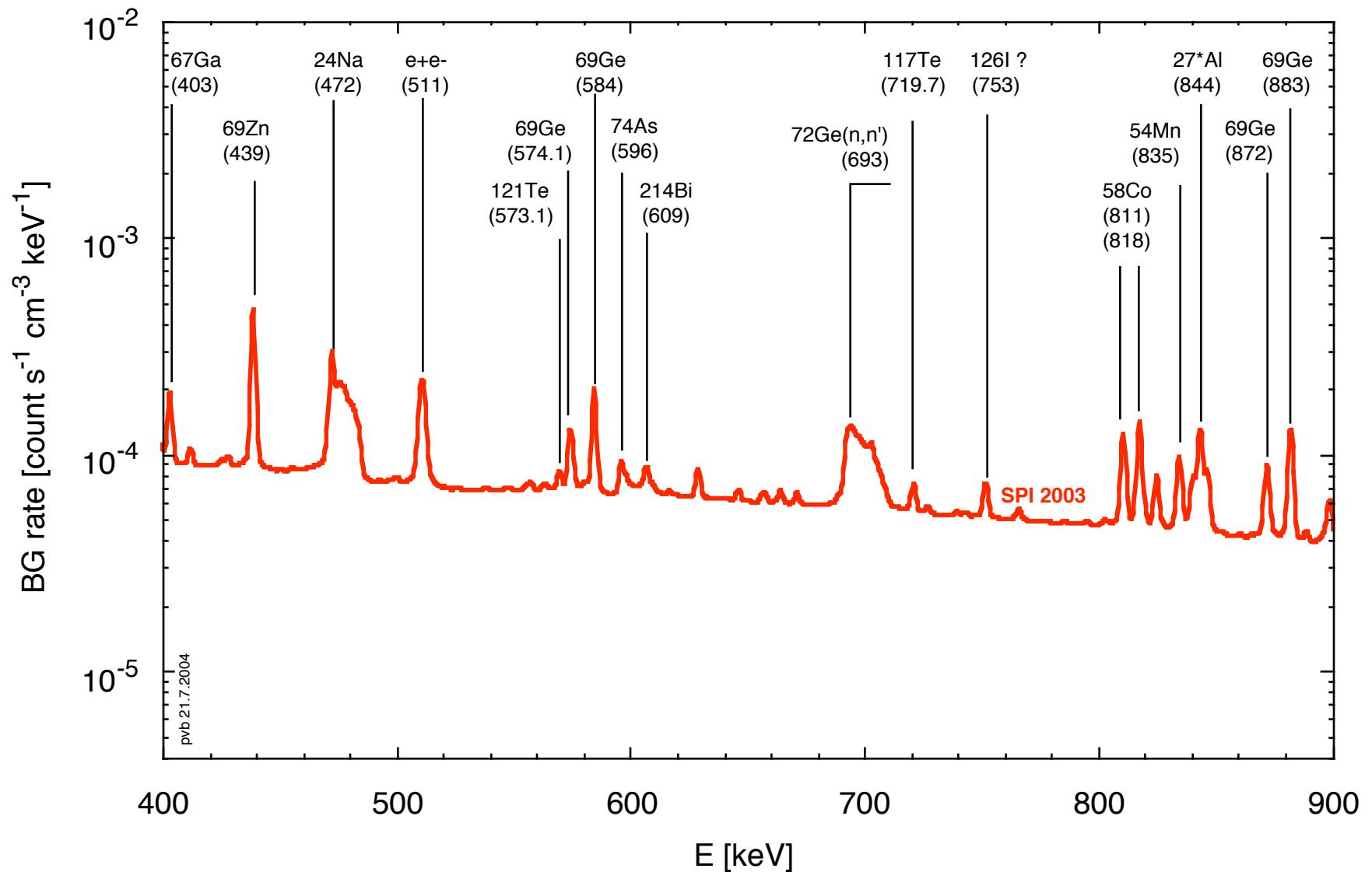
- converts CR p

reduces lifetime

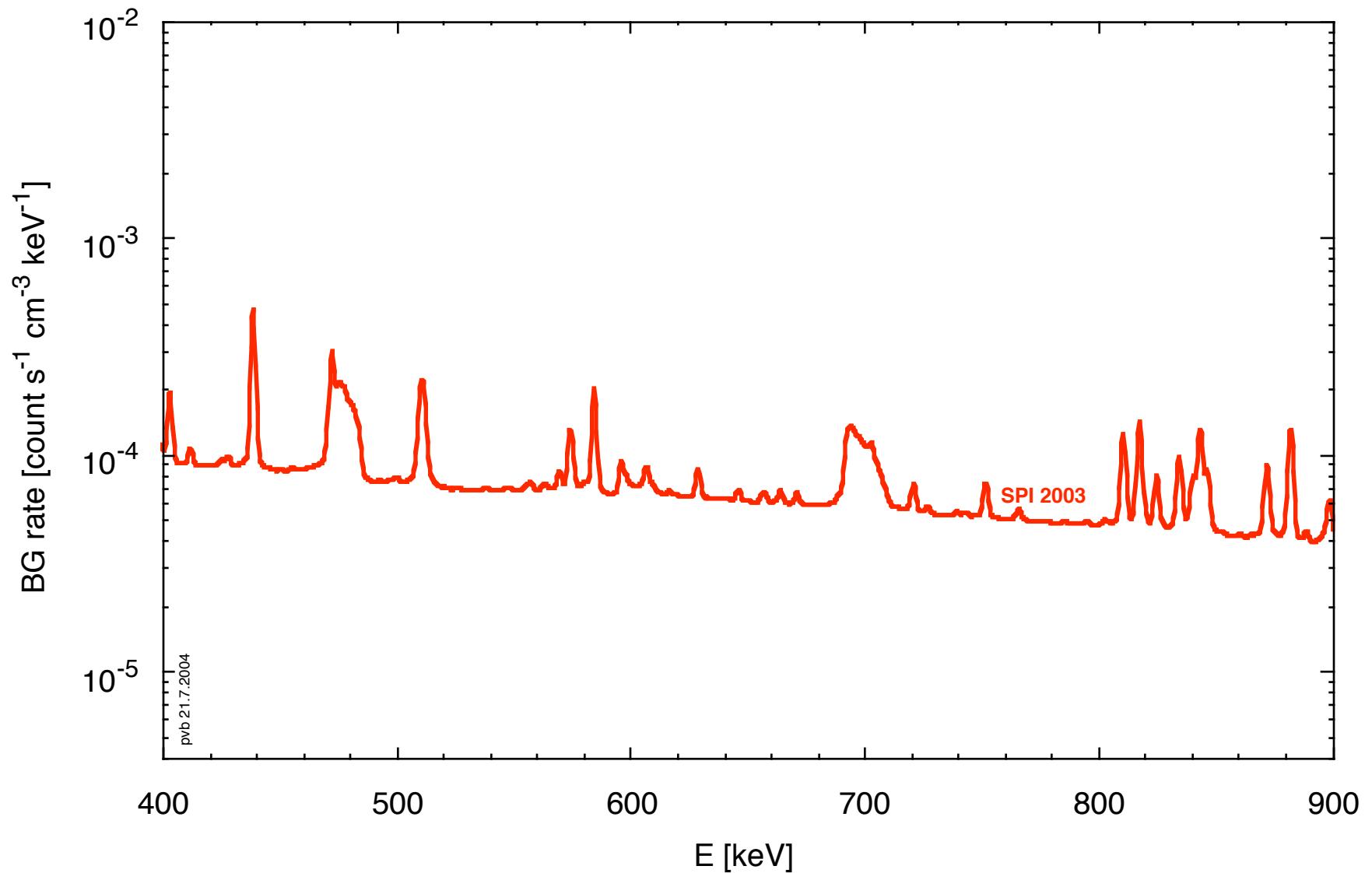
implicitly reduces effective area : with limited mass budgets in balloon and satellite experiments, a shield is most likely the heaviest part of the instrument

( *INTEGRAL SPI shield ACS : 856 kg ; BGO alone : 504 kg  
detector camera : 141 kg ; Ge alone : 19 kg* )

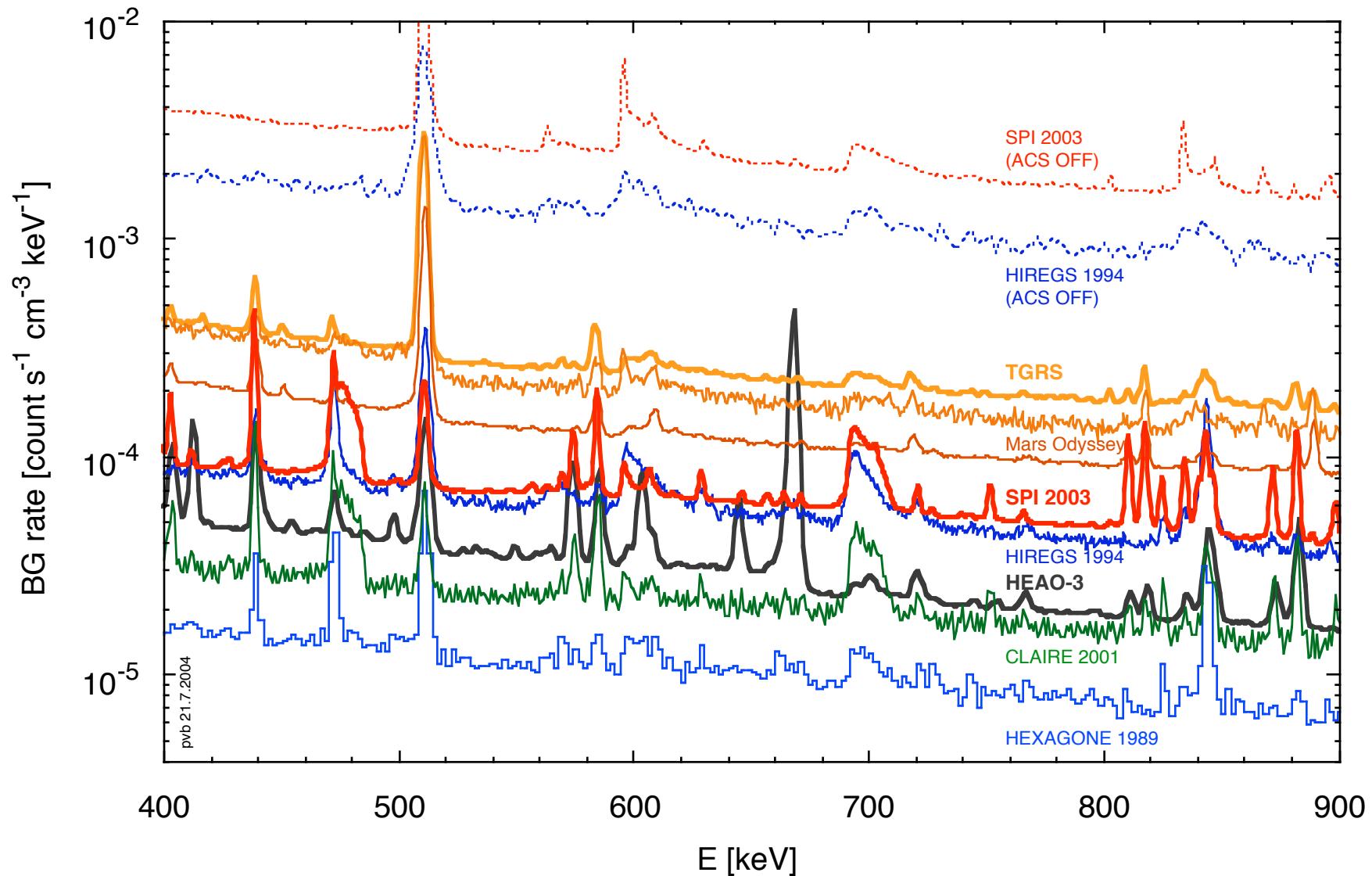
# Ge detector background : SPI



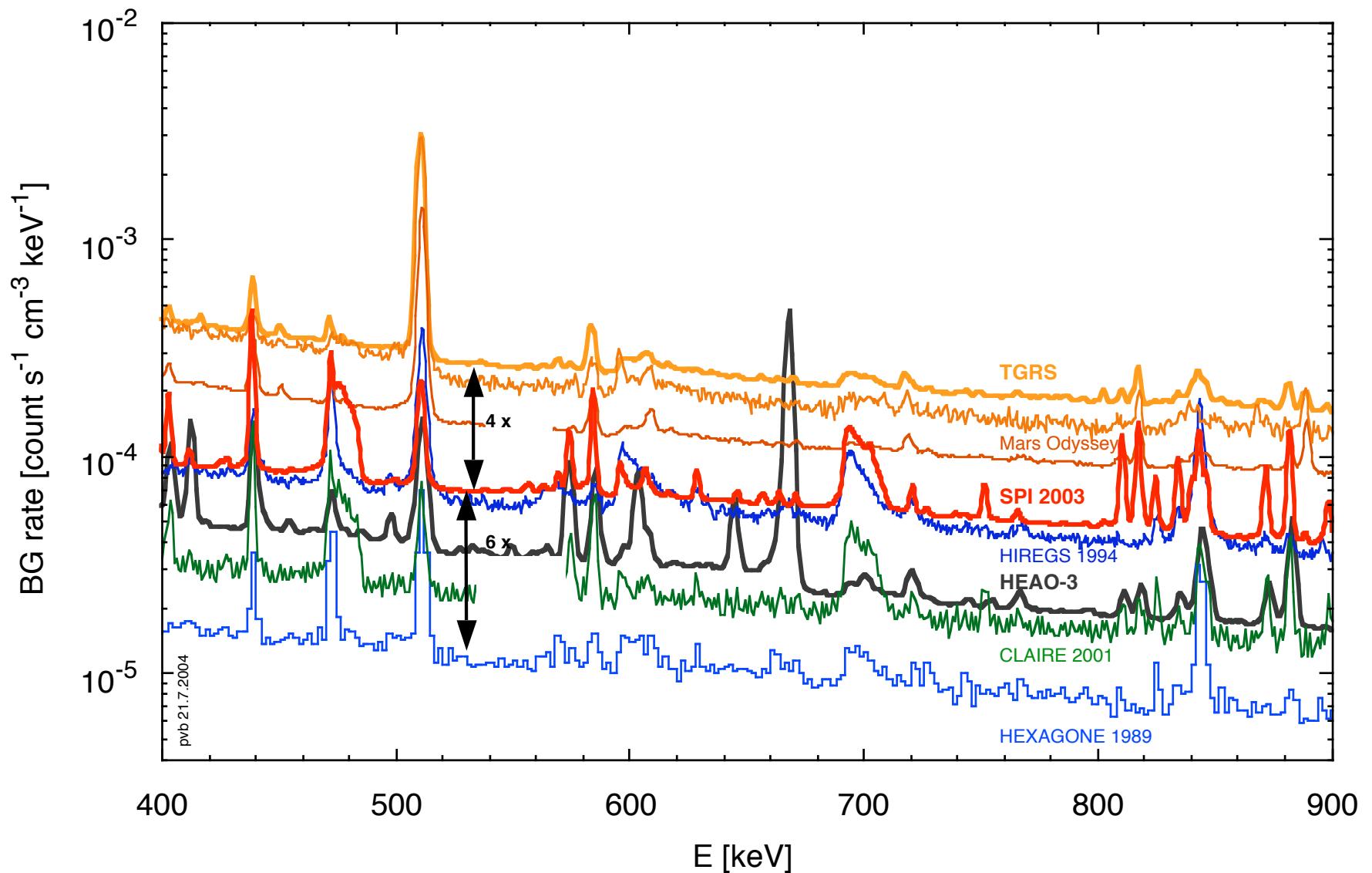
## Ge detector background : SPI



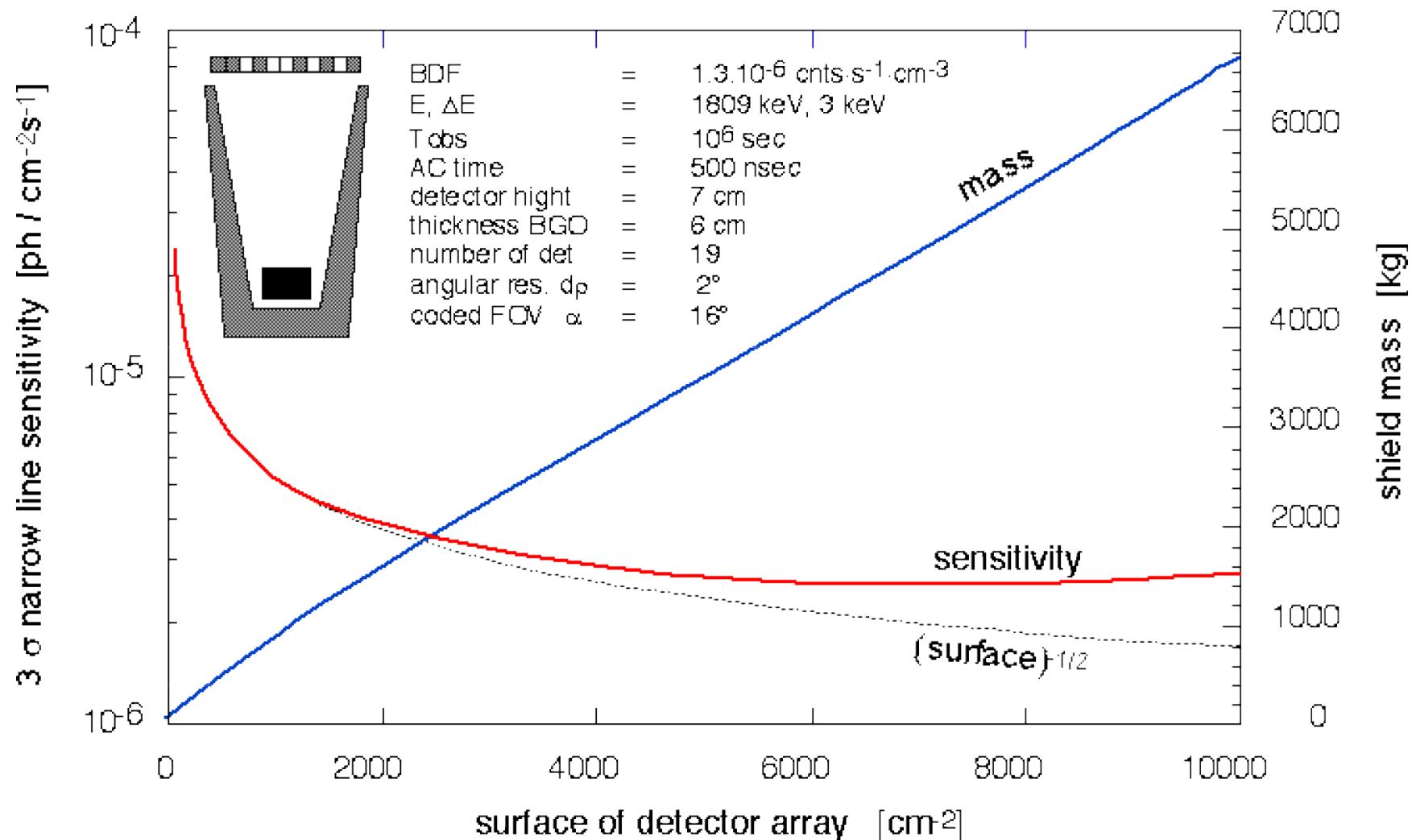
# Ge detector background : comparison



# Ge detector background : comparison



# Anticoincidence shields - the limit of growth



## ACT/GRI sensitivity requirement

$$f_{3\sigma} < 5 \cdot 10^{-7} \text{ s}^{-1} \cdot \text{cm}^{-2}$$

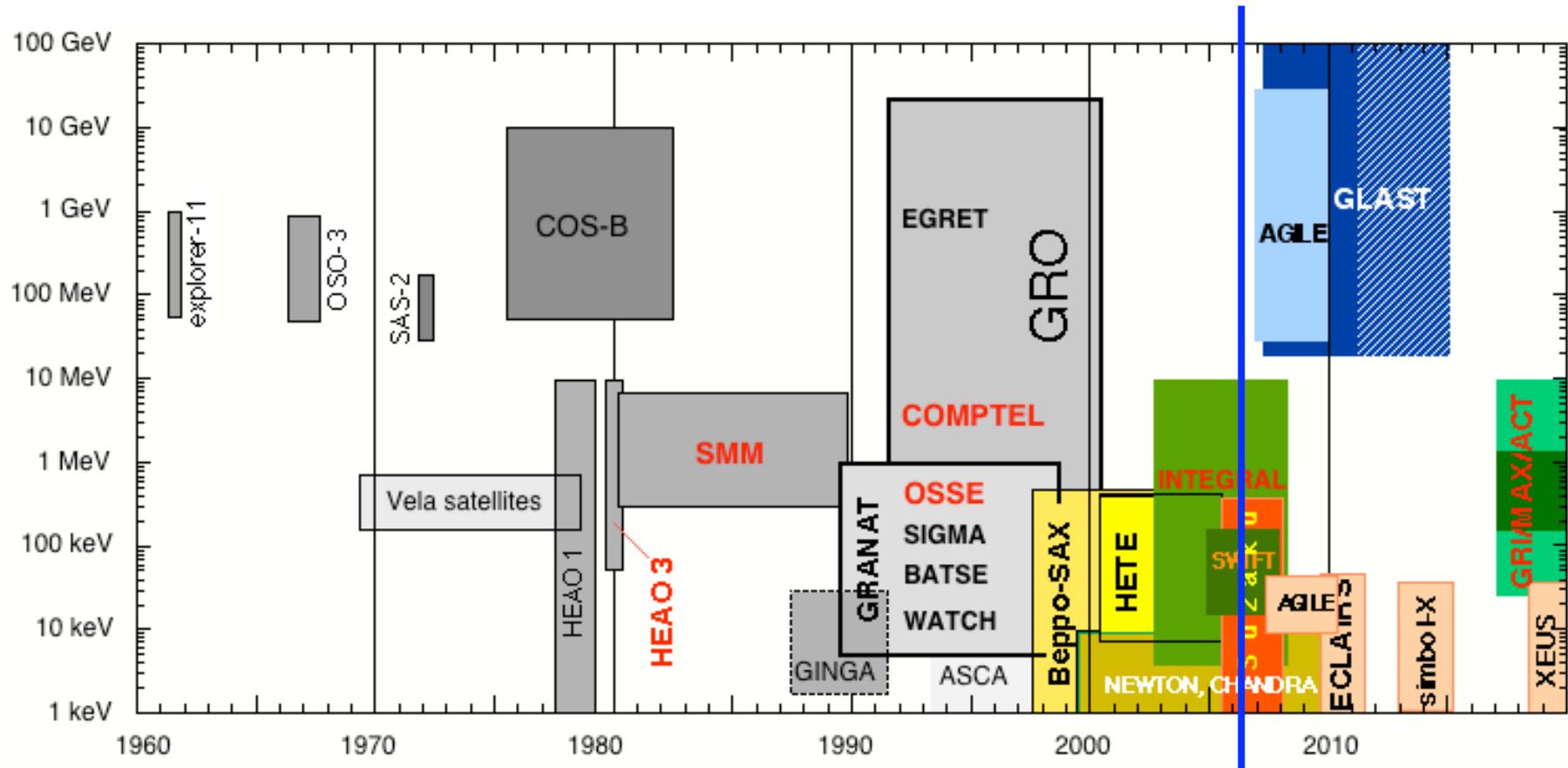
**$f_{3\sigma} < 5 \cdot 10^{-7} \text{ s}^{-1} \cdot \text{cm}^{-2}$  !**

**You must be kidding**

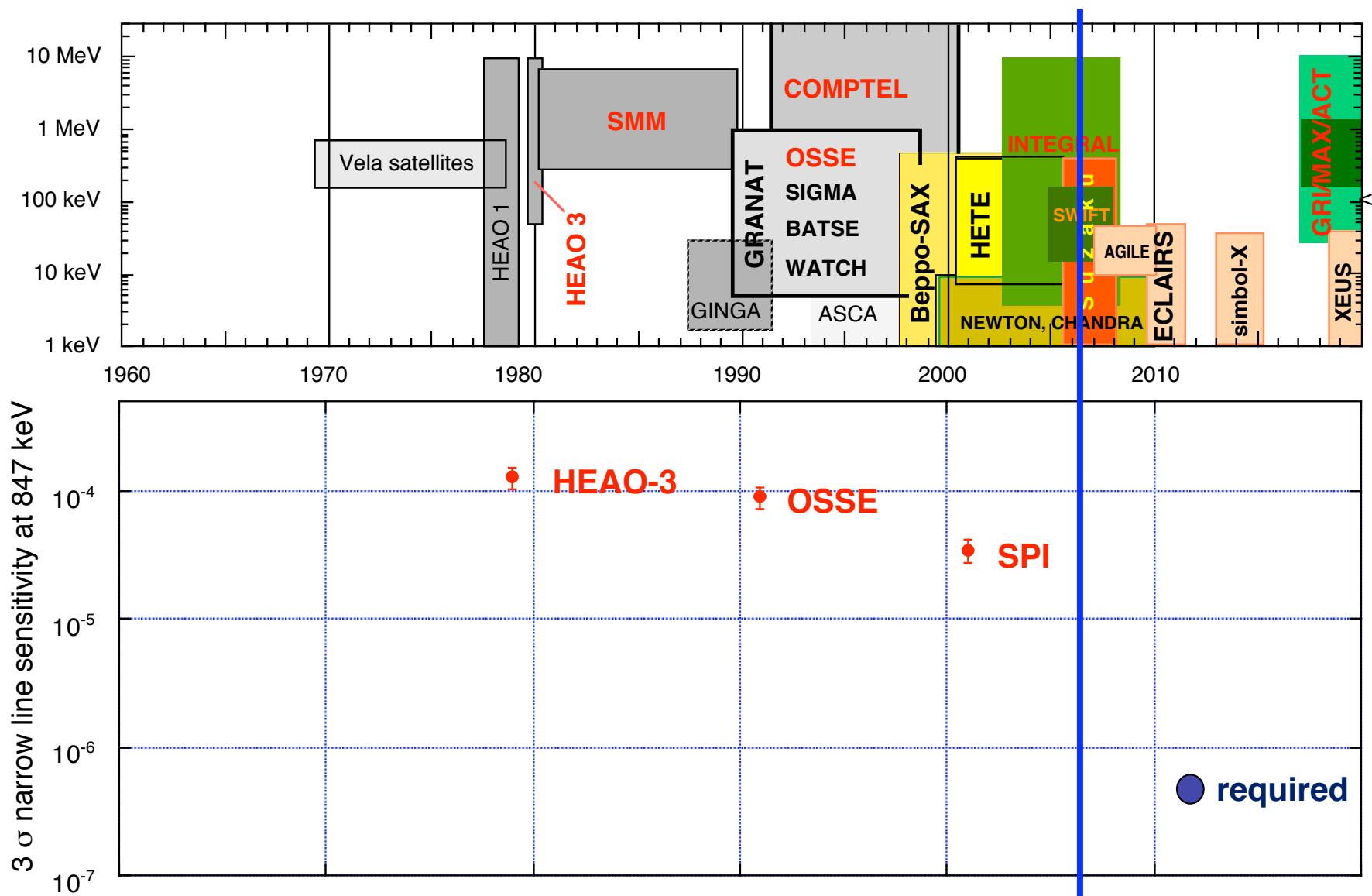
this means : ~ **one photon per cm<sup>2</sup> every month**

with a BG produced by **one CR particle per cm<sup>2</sup> per second**  
producing eg at 511 keV (SPI) ~ **a BG event per cm<sup>2</sup> every 3 minutes**

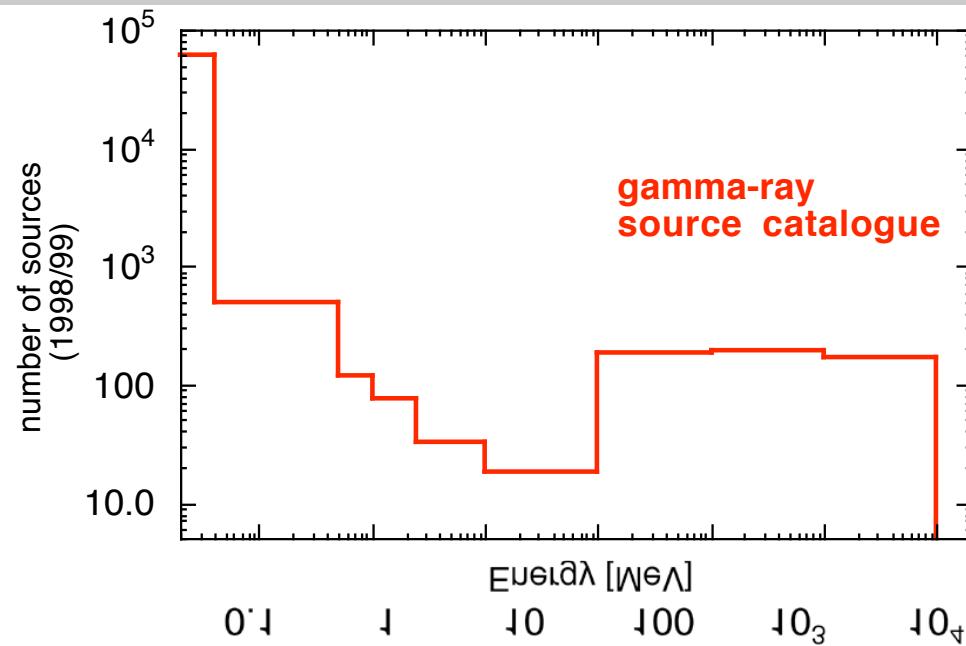
# Past, present, and future observations in gamma-ray lines



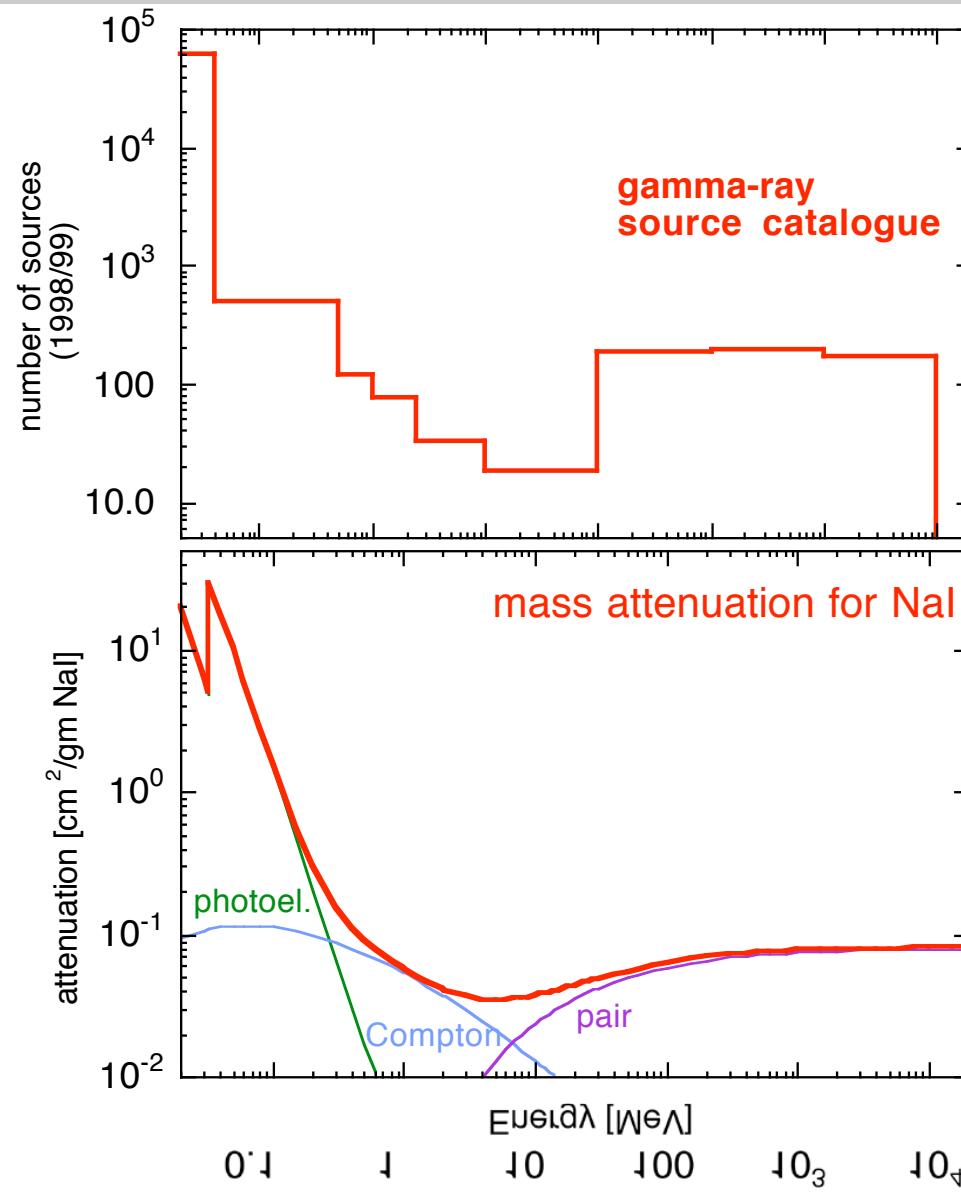
# Past, present, and future observations in gamma-ray lines



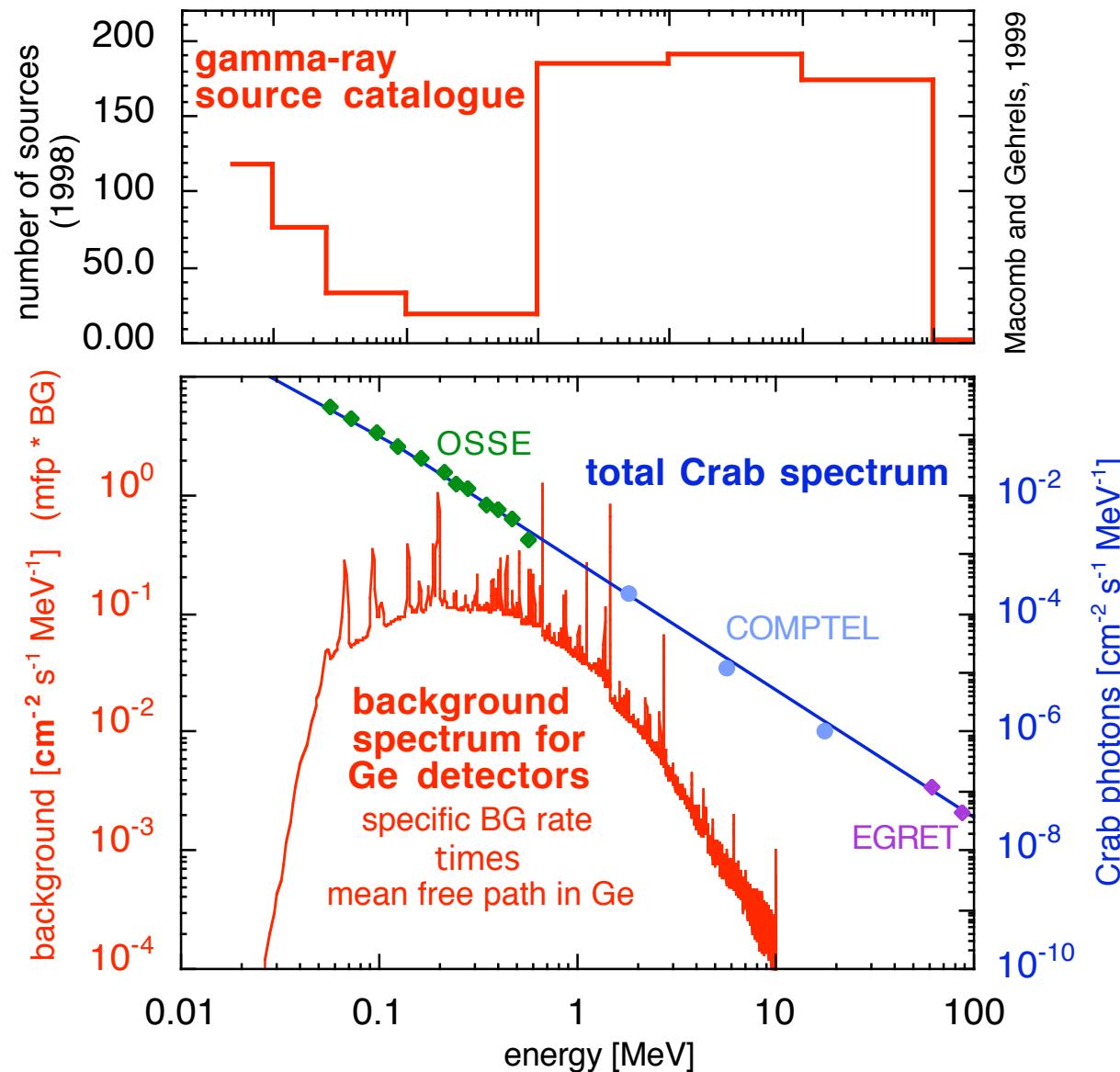
# Gamma-ray source statistics



# Gamma-ray source statistics



# Gamma-ray source statistics



# Improving sensitivity

the detectable minimum flux will depend on the

Collecting area (for optical thick/thin detectors : detecting surface/volume)

Detection efficiency

Effective exposure time

Background

$$f_n \approx n \cdot (N)^{1/2} / X \approx n \cdot (b V T_{\text{obs}})^{1/2} / A_{\text{eff}} T_{\text{obs}}$$

Building on present technology and measured BG spectra, the narrow line sensitivity of an instrument with e.g.  $A_{\text{eff}} = 2000 \text{ cm}^2$  ( $A_{\text{geo}} \approx 1 \text{ m}^2$ ) scales with respect to :

	$A_{\text{eff}}$	$f_{3\sigma}$	$f_{3\sigma}$ ( $X = A_{\text{eff}} T_{\text{obs}} = 2 \cdot 10^9 \text{ cm}^2 \text{s}$ )
OSSE	$450 \text{ cm}^2$ (662 keV)	$8 \cdot 10^{-5}$	$4 \cdot 10^{-5} \text{ [ph cm}^{-2} \text{ s}^{-1}\text{]}$
COMPTEL	$20-50 \text{ cm}^2$ (2 MeV)	$4 \cdot 10^{-5}$	$6 \cdot 10^{-6} \text{ [ph cm}^{-2} \text{ s}^{-1}\text{]}$
SPI	$100 \text{ cm}^2$ (847 keV)	$2 \cdot 10^{-5}$	$4 \cdot 10^{-6} \text{ [ph cm}^{-2} \text{ s}^{-1}\text{]}$

but how to get the ACT GRI requirements of  $\sim 5 \cdot 10^{-7} \text{ [ph cm}^{-2} \text{ s}^{-1}\text{]}$  ?

